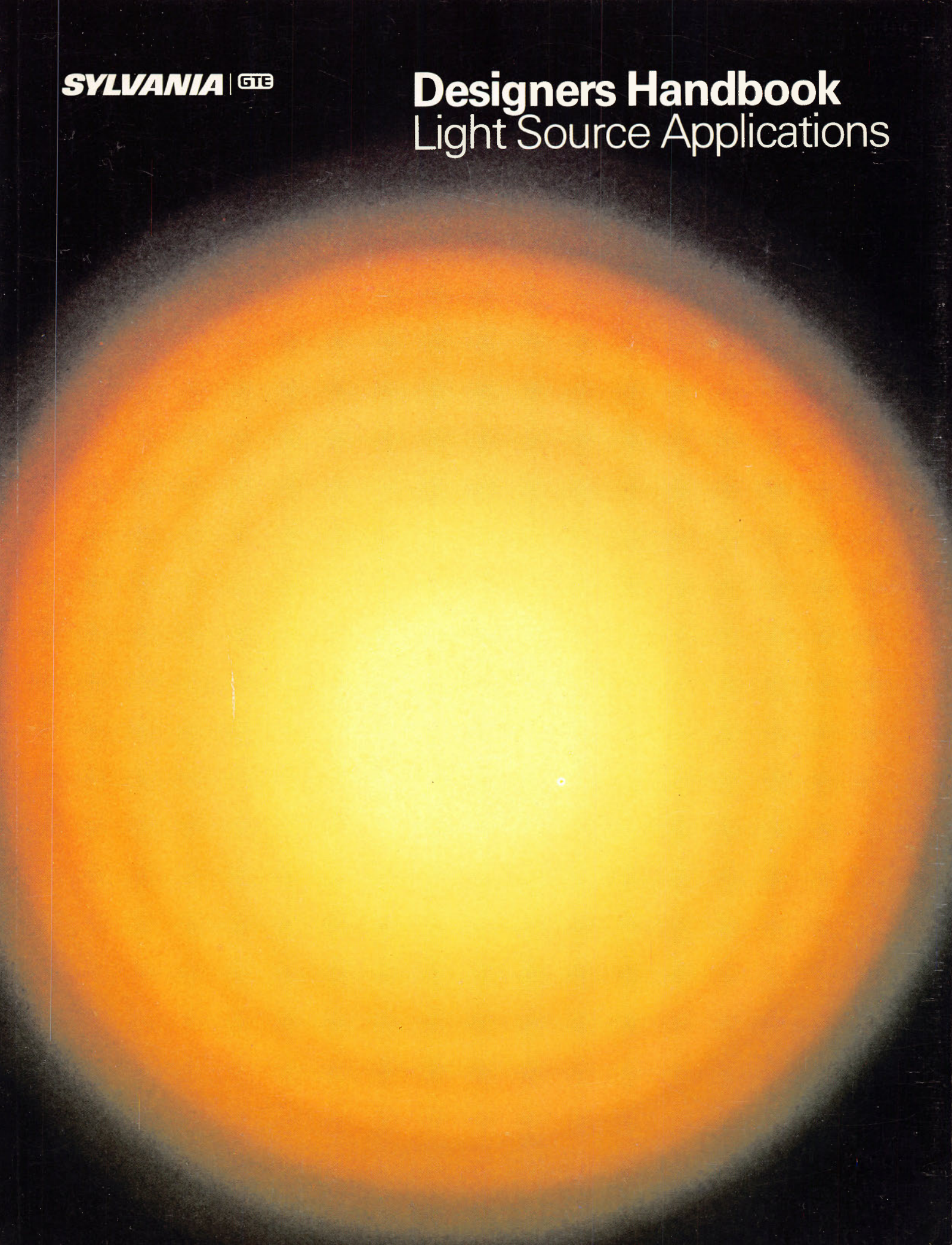
SYLVANIA | GTE

Designers Handbook
Light Source Applications



Introduction

The need for a technical handbook with an overview of lighting and light sources has been voiced by many segments of the electrical industry and, in particular, those businesses involved in the manufacture and application of photographic, reprographic, and micrographic equipment. This handbook has been prepared with these specific needs in mind.

Due to the very large number of individual lamp types available, no attempt has been made to catalog them in this publication. Only a few lamps of each general type have been mentioned as examples. The reader is referred to current catalog literature for complete listings of lamps and their specifications.

We believe that this handbook will be of value to engineers in design, manufacturing and quality control, designers, engineering students, technicians, and others involved in the use of radiant energy sources. As new ideas are usually developed from a broad base of knowledge, the purpose of this book is twofold: (1) To present an overview of currently available products, a review of how they work, and a summary of application techniques; and (2) To stimulate new ideas, new approaches, and new products that will broaden our fields of knowledge and application.

Many members of the Lighting Products Group have contributed to the preparation of this handbook; special recognition is due to R. Reid, M. Brickett, J. Lumia, T. Sadoski, and H. Milke.

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1.0 Introduction and Overview of Light Sources

Incandescent Lamps

This group of lamps generates optical radiation by electrically or chemically heating metal filaments to temperatures (above approximately 850K) at which those filaments become incandescent, i.e., they emit visible radiation (light).

Tungsten-filament lamps have filaments of tungsten wire heated to incandescence by the passage of electric current through those filaments. These lamps may be completely evacuated, or may be filled with an inert gas (e.g. nitrogen, argon, or krypton) to retard evaporation of tungsten from the filament.

Tungsten-halogen lamps are tungsten-filament incandescent lamps filled with an inert gas to which a trace of halogen vapor (e.g., iodine or bromine) has been added. These lamps operate at temperatures permitting the functioning of a halogen regenerative cycle which removes evaporated tungsten from the bulb wall. The bulb-wall operating temperatures must be so high (above approximately 250°C) that fused quartz or high-temperature glass is employed as the bulb material. Tungsten-halogen lamps may be designed to have much longer life than non-halogen incandescent lamps of equal luminance and efficacy, or they may be designed to have greater luminance and efficacy than non-halogen incandescent lamps of equal life ratings.

Photoflash lamps are incandescent lamps that employ the combustion of a metallic foil, (e.g., zirconium or hafnium) in an oxygen atmosphere to produce intense flashes of light for brief duration (e.g., tens of milliseconds). They are available as single flashbulbs, or as assemblies of four, eight, or ten flashbulbs with built-in reflectors and automatic switching from the last fired flashbulb to the next unfired flashbulb.

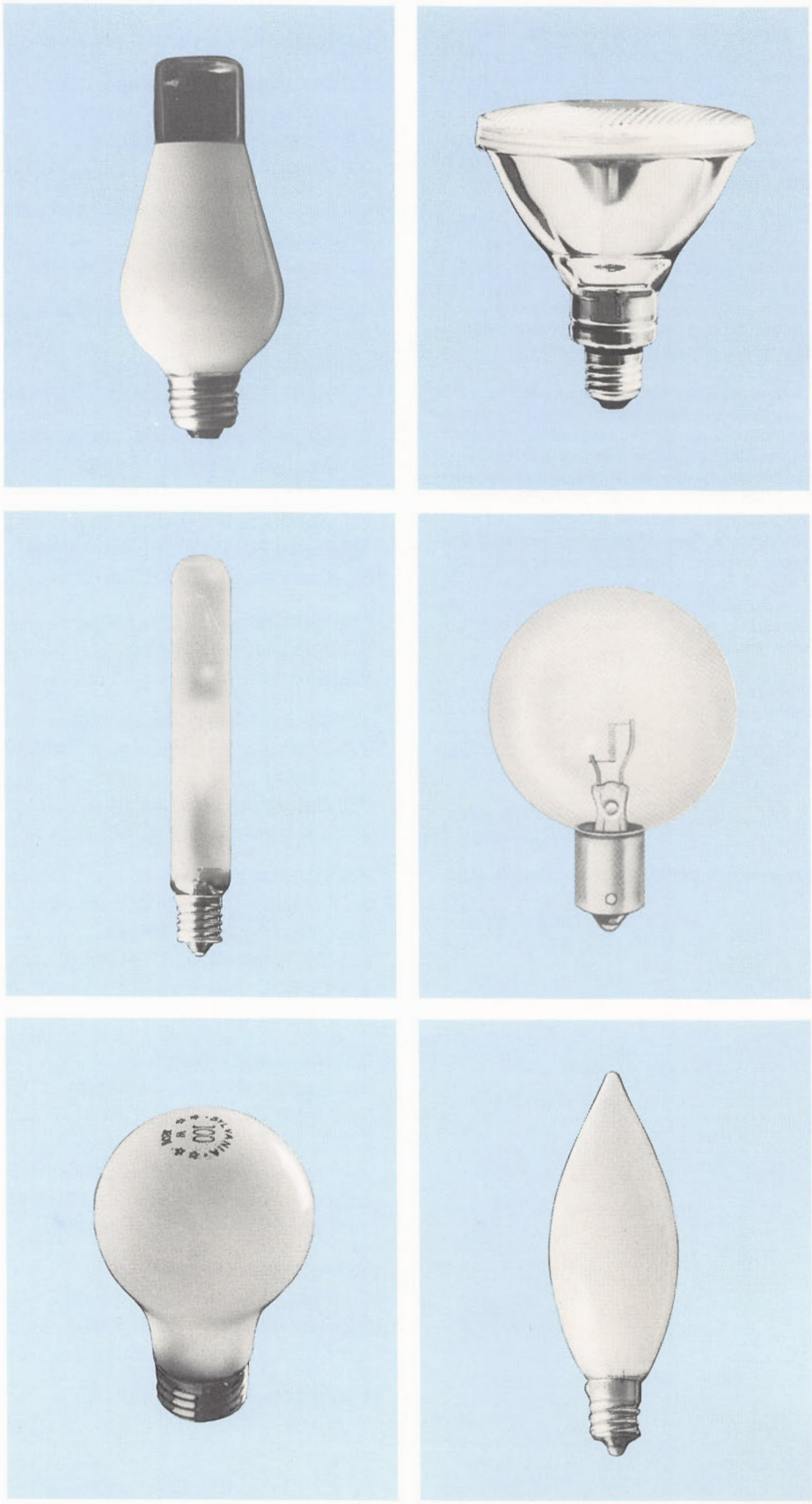

Figure 1.0-1 Typical tungsten-filament incandescent lamps.

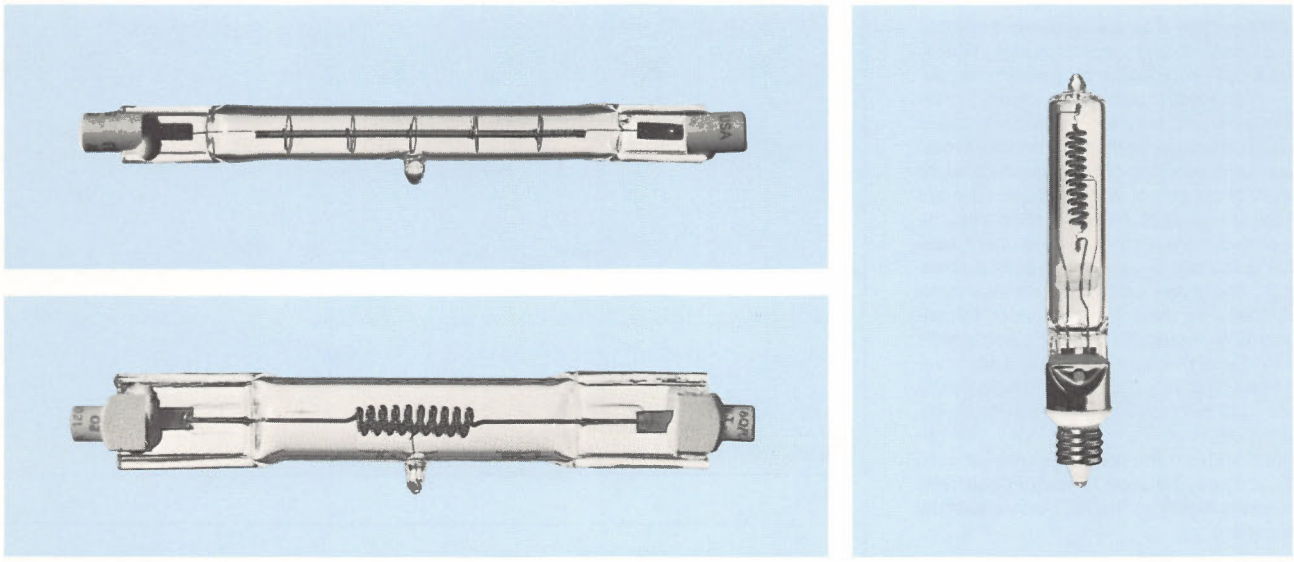

Figure 1.0-2 Typical tungsten-halogen incandescent lamps.

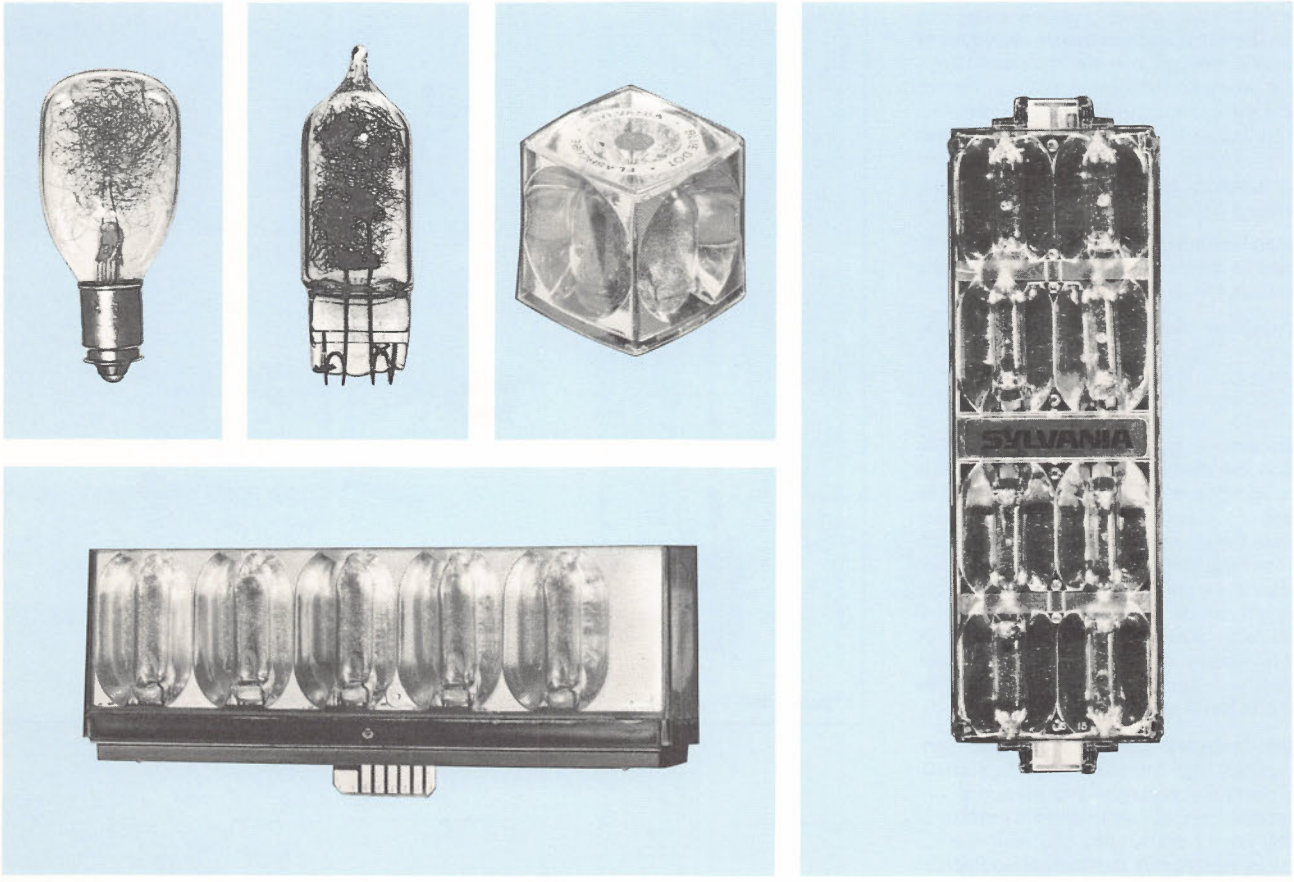

Figure 1.0-3 Typical photoflash lamps.

Gaseous Discharge Lamps

This large group of lamps, also called electric-discharge lamps and arc-discharge lamps, generates optical radiation by passage (or discharge) of an electric current through an ionized gas (e.g., argon, krypton, neon, or xenon) or vapor (e.g., mercury, sodium, or metal halides) to cause luminescence of the gas or vapor by excitation of its atoms or molecules. The arc discharge takes place between electrodes inside a sealed transparent or translucent bulb containing the gas or vapor. The optical radiation (e.g., line, band, and/or continuous spectra) produced by the luminescence of the excited atoms or molecules is determined mainly by the kind and pressure of the gas and/or vapor and additives (e.g., metal halides) contained in the bulb, but may be modified by the spectral transmission of the bulb material. The optical radiation from the discharge may be used directly or it may be used to excite phosphors that generate radiation having desired spectral distributions.

Most gaseous-discharge lamps require auxiliary electrical apparatus of some kind to start the arc and to limit the arc current after starting. The voltage required to initiate the arc is greater than the operating voltage required to maintain the arc so that a starting circuit is needed. Also, electric arcs generally have current-voltage characteristics with negative-resistance regions in which the voltage across the arc decreases as the current through the arc increases. Such negative-resistance characteristics can lead to runaway and destruction of the lamp unless the current is limited to rated values by an external series impedance. Both starting and current-limiting functions are usually provided by a device called a ballast.

Gaseous-discharge lamps are categorized by designers in terms of their internal operating pressures as follows.

Low-pressure discharge lamps operate at pressures in the order of 0.001 atmosphere, with loadings in the order of 0.5 to 2W/cm of arc length, and with spectral outputs consisting of the narrow lines or bands characteristic of the elements (e.g., mercury or sodium) involved in the discharge. The spectral outputs may be significantly modified by coating the inside wall of the bulb with a phosphor which is excited to fluorescence by the optical radiation from the discharge. This group includes: fluorescent lamps for general illumination; fluorescent lamps with narrowband spectral outputs (e.g., super diazo blue, blacklight, or green) for various special applications; reflector and aperture fluorescent lamps, germicidal lamps; and low-pressure sodium lamps.

Medium-pressure discharge lamps, generally called high-intensity discharge (HID) lamps, operate at pressures in the range of 1 to 10 atmospheres, with loadings in the order of 20 to 200W/cm of arc length, and emit a small amount of continuous radiation in addition to spectral lines and/or bands. HID lamps comprise small arc tubes usually mounted inside glass outer jackets which are either evacuated or filled with inert gas to prevent oxidation of

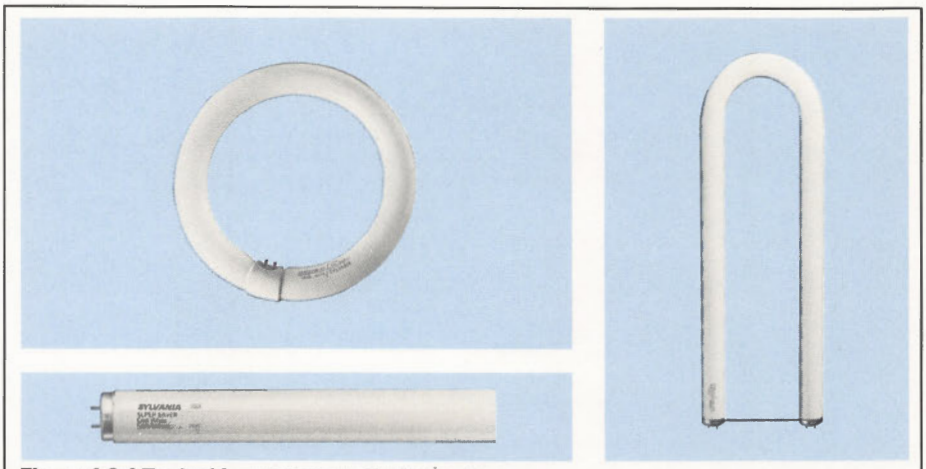

Figure 1.0-4 Typical low-pressure discharge lamps.

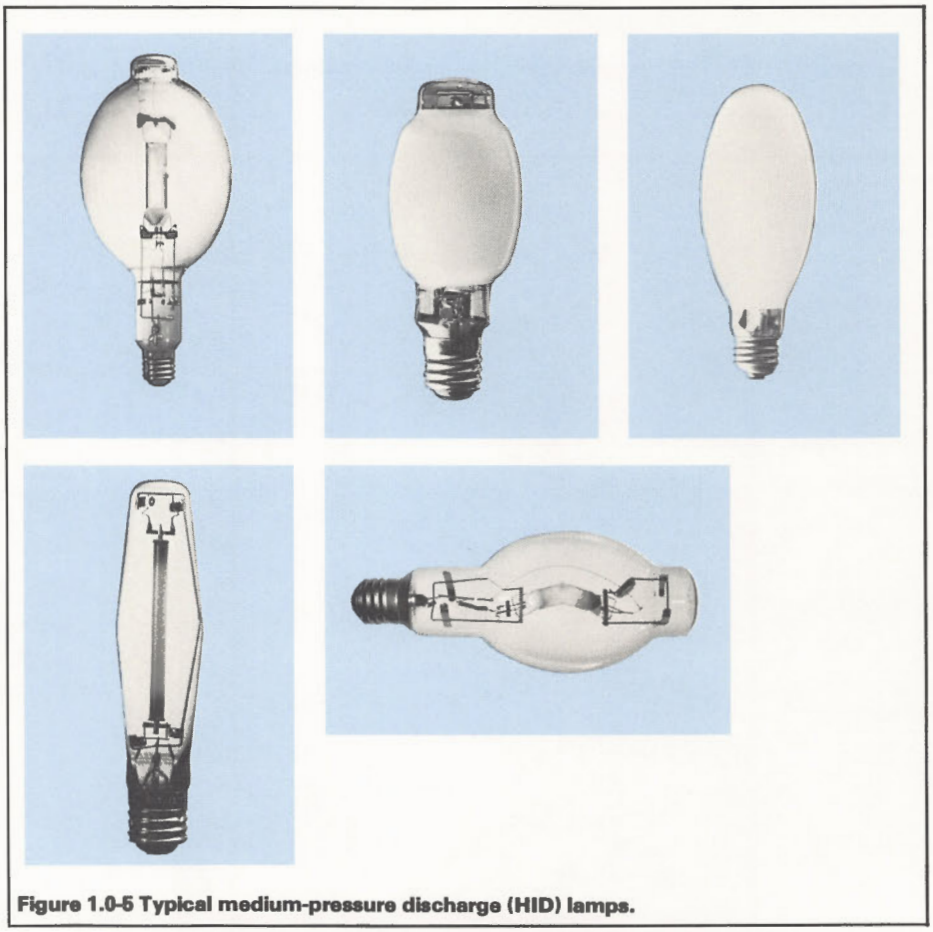

Figure 1.0-5 Typical medium-pressure discharge (HID) lamps.

the arc-tube lead seals. The jacketed HID group includes mercury (uncoated, or with phosphor-coated outer bulb), metal-halide (Metalarc, Super Metalarc, and Swingline), and high-pressure sodium (HPS) lamps. Unjacketed tubular mercury and metal-halide lamps are available in lengths up to 2 meters for photochemical, reprographic, and special lighting applications.

High-pressure discharge lamps, also called compact-arc or short-arc lamps, operate at pressures above 10 atmospheres, with loadings in the order of kilowatts/cm of arc length, and emit large amounts of spectrally-continuous radiation. This group includes mercury, mercury-xenon, xenon, metal-halide, and Colorarc short-arc lamps.

Electronic Flash Lamps

These gaseous-discharge lamps are designed to generate brief flashes of light when energy stored in external capacitors is discharged through them. This group includes xenon flashtubes and strobotrons.

Special Purpose Lamps

This group includes zirconium-cathode and tungsten-cathode concentrated-arc lamps, deuterium-arc lamps, and glow-modulators.

Luminance and Efficacy of Light Sources

Figure 1.0-9 is a bar chart showing luminance and efficacy limits of most of the types of lamps described, as well as of miscellaneous sources such as electroluminescent panels and light-emitting diodes. Luminance and efficacy are two of the most significant parameters by means of which light sources can be evaluated and compared, and Figure 1.0-9 shows typical state-of-the-art upper limits of those parameters for most presently available types of light sources. Note that the luminance values are averaged over the principal spatial radiating region of each type of source.

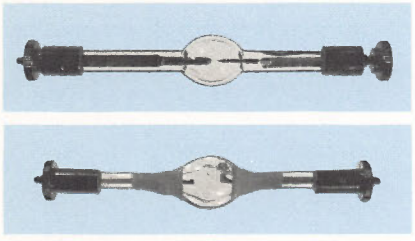

Figure 1.0-6 Typical high-pressure discharge (short-arc) lamps.

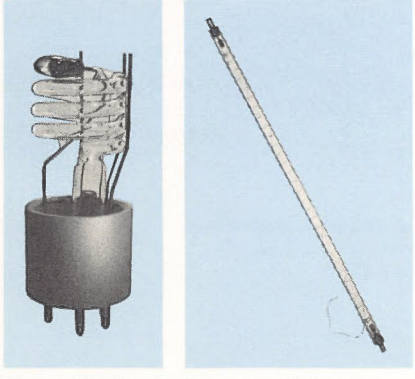

Figure 1.0-7 Typical electronic flash lamps.

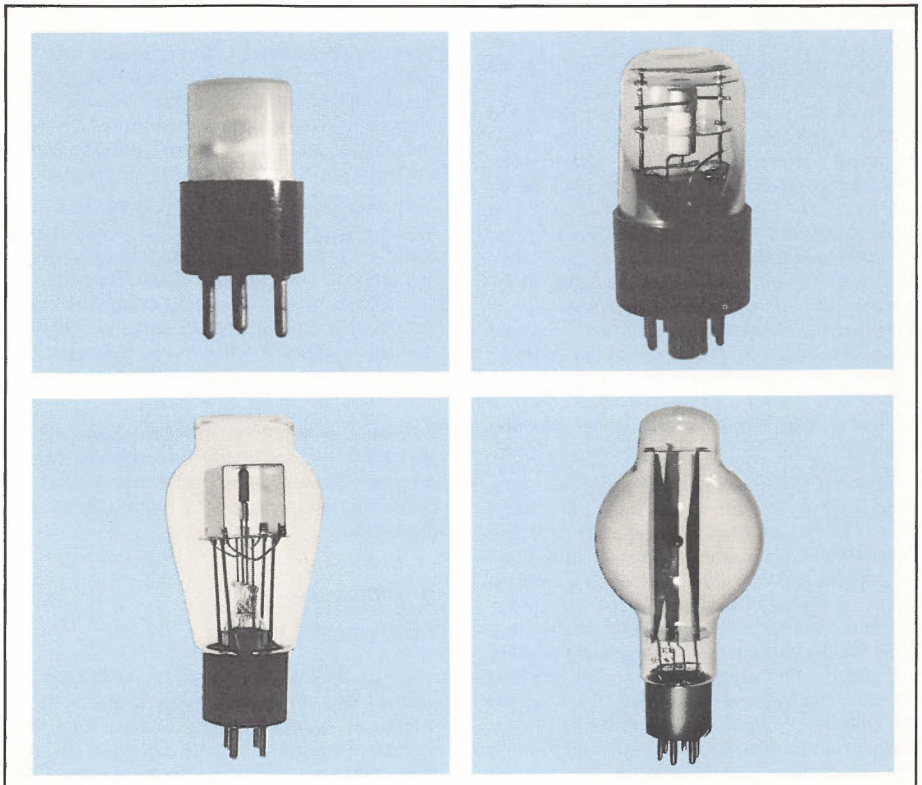

Figure 1.0-8 Some special purpose lamps.

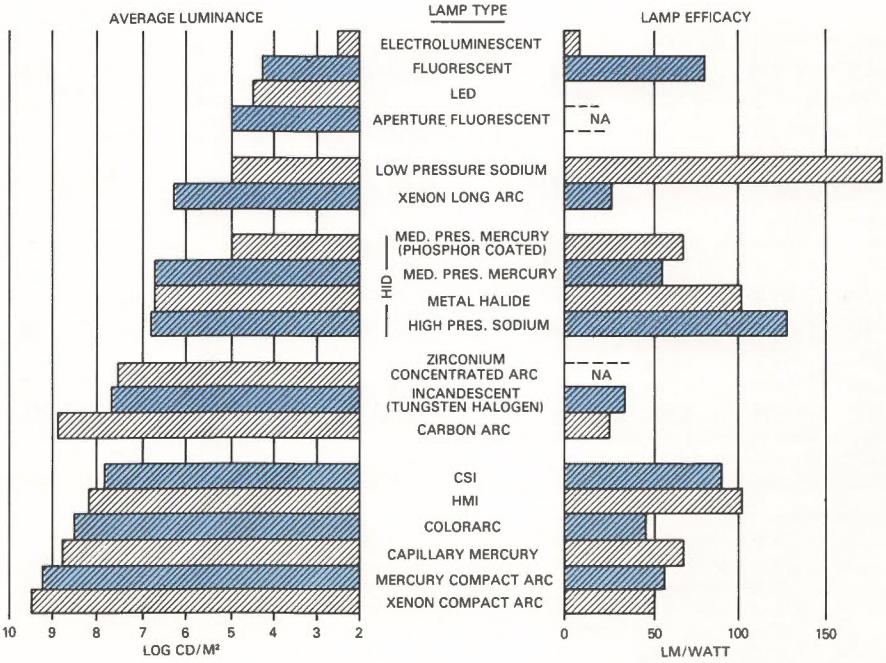

Figure 1.0-9 State-of-the-art luminance and efficacy limits of various types of light sources. The luminance values are averaged over the principal spatial radiating region of each type of source.

2.0 Incandescent Lamps

The usual incandescent lamp consists of a refractory conductive filament sealed within a light-transmitting envelope or bulb that is either evacuated or filled with an inert gas. Lead-in wires from the ends of the filament pass through the seals so that the filament may be connected to a source of electricity. The filament is heated by the electrical power supplied to it and emits electromagnetic radiation. If the electrical power is sufficient to raise the filament temperature above approximately 850K, the filament becomes incandescent, i.e., it radiates sufficient power in the visible region of the spectrum (380-760nm) to be seen by its own radiation. The amount of light produced by incandescence increases with the temperature of the filament. However, the life of incandescent lamps is reduced as the filament temperature increases, so that one fundamental problem of incandescent lamp design becomes that of achieving high light output while retaining reasonable life.

Edison's first successful incandescent lamp employed a filament of carbon, the melting point (3823K) of which is higher than of any other element. However carbon filaments could not be operated at temperatures high enough to obtain desirable efficacies without rapid evaporation of the carbon, causing bulb blackening, early filament failure, and thus greatly shortened lamp life. The efficacy of the carbon-filament lamp was limited to the low value of 1.4 lumens per watt (lm/W or LPW). The efficacy of incandescent lamps was gradually improved through the use of new filament designs and new filament materials such as osmium and tantalum, but tungsten replaced all previous filament materials after 1911 when a practical process for drawing tungsten wire was perfected.

The first tungsten-filament lamps (1911) were vacuum lamps which achieved efficacies of 10 lm/W. The introduction of inert-gas fills and coiled filaments (1913) permitted efficacies of 14 lm/W. Subsequent developments have resulted in efficacies up to 23 lm/W in large commercial types and up to 35 lm/W in short-life photographic type lamps. The value of 35 lm/W is the practical upper limit set by losses within the lamp and the melting point of tungsten.

The tungsten-filament lamp costs less than most other types of lamps and is versatile, being made in a multitude of sizes, configurations, and ratings. There are about 500 different types and several thousand catalog listings by variations such as voltage, finish, and base. Despite the development of other types of lamps, the tungsten-filament lamp is expected to remain a basic light source for a long time.

The tungsten-halogen lamp described in Section 2.2 is a more recent development of the tungsten filament lamp and is being used increasingly in micro/photo/repro-graphic applications.

2.1 Tungsten Filament Lamps

Tungsten has the highest melting point (3655K) and the lowest vapor pressure of all metals at elevated temperatures. Tungsten filaments therefore can be operated at high temperatures with low evaporation rates. This combination of properties is desirable since low evaporation rates permit extended filament life while high filament temperatures result in high lumen outputs and efficacies. The variation of lumen output and efficacy with filament temperature is shown in Figure 2.1-1 which compares significant data for 120-volt tungsten-filament lamps with ratings from 6 watts to 1500 watts. Note that the lamps of higher wattage ratings operate at higher filament temperatures with corresponding increases of color temperature, lumen output, and efficacy in lumens per watt.

Physical Characteristics

Typical Construction Features

Figure 2.1-2 shows the construction details of a typical tungsten-filament incandescent lamp. Details vary with wattage and type of application. The tungsten filament is supported on an inner structure that is sealed to the bulb at the bottom and capped by a base. Bulbs are generally made of soft glass, but hard glass is used for lamps operating at higher temperatures as well as for lamps having increased resistance to breakage. The entire inner structure comprising the filament, lead-in, and support wires is supported within the bulb by a glass stem which is fused to the end of the bulb neck and which projects through the tubular neck nearly into the spherical portion of the bulb.

The tungsten filament, which may be a coiled wire or a coiled-coil wire, is located near the center of the spherical portion of the bulb. It is supported at its ends by the lead-in wires that carry current from the base to the filament and at one or more intermediate points by support wires. The lead-in wires from the base to the

RATED WATTS (a)	BULB TYPE	FILAMENT FORM	INRUSH CURRENT PEAK AMPERES (b)	INRUSH CURRENT DECAY TIME, MILLISEC. (c)	INCANDESCENCE TIME MILLISEC. (d)	NIGRESCENCE TIME MILLISEC. (e)	APPROX. COLOR TEMP., DEGREES K (f)	APPROX. INITIAL LUMENS	EFFICACY, LUMENS PER WATT
6	S14	C9	0.57	25	50	15	2370	40	6.7
10	S14	C9	0.96	40	85	30	2450	80	8.0
25	A19	C9	3.8	75	140	55	2550	235	9.4
40	A19	C9	6.4	50	90	35	2770	460	11.5
60	A19	CC8	9.8	60	110	50	2800	890	14.8
100	A19	CC8	17	80	150	60	2870	1740	17.4
150	A21	CC8	25	110	190	80	2900	2885	19.2
200	A23	CC8	35	120	220	95	2930	3940	19.7
300	PS30	C9	54	150	280	120	2940	5960	19.9
500	PS35	CC8	90	210	400	160	2960	10445	20.9
1000	PS52	CC8	180	270	570	240	3030	23100	23.1
1500	PS52	C7A	270	360	680	300	3070	33620	22.4

NOTES:

(a) The 6W, 10W, and 25W lamps are vacuum lamps. The others are gas-filled.

(b) Theoretical value based on hot-to-cold resistance. Actual value may be less depending on power source impedance characteristics. The maximum current occurs near the first peak of voltage and so may be delayed several milliseconds after voltage is applied.

(c) Time for initial inrush current to decrease to 110% of normal current with lamp energized at peak of voltage wave.

(d) Heating time to 90% lumens.

(e) Cooling time to 10% lumens.

(f) Filament temperature is usually within 100K of color temperature.

Figure 2.1-1 Comparative data for typical 120V tungsten-filament incandescent lamps.

stem press are generally made of copper, and those from the stem press to the filament are generally made of nickel or nickel-plated copper. The lead-in wires that pass through the stem press are made of Dumet, a composite of a copper sheath over a nickel-iron alloy core, which has almost exactly the same temperature coefficient of expansion as the glass of the stem press. This assures an unbroken hermetic seal over a lifetime of cycling between ambient and operating temperatures.

Projecting up from the stem press is a molybdenum support wire which constrains the filament at a point midway between its ends to reduce sagging at operating temperatures.

An exhaust tube inside the glass stem provides means for evacuating the bulb, for flushing the bulb with a gas such as nitrogen, and finally for filling the bulb with an inert gas such as argon or an argon-nitrogen mixture at a pressure of about 80% of atmospheric. The exhaust tube, which initially projects beyond the end of the neck, is sealed after evacuation and filling and is then cut off to permit attachment of the base to the bulb.

The base provides the means of supporting the lamp in its socket and also provides electrical contacts that permit current flow between the socket and the filament. The typical screw base shown has a center contact and a metal shell which are separated by electrical insulation material. The base is cemented to the bottom of the bulb; then one lead-in is soldered to the center contact and the other lead-in is soldered or welded to the upper rim of the base shell. In lamps designed to operate at high base temperatures, both lead-ins are welded and the base is mechanically fastened to the bulb without cement.

In some general service lamps of higher wattage ratings, a heat deflector is located so as to reduce heat losses by minimizing circulation of hot gas into the neck of the bulb. Some lamp types have internal fuses in the stem to protect power sources by opening if the filament arcs.

In the particular configuration shown in Figure 2.1-2, the filament is mounted along the vertical axis of the lamp. Although filaments may be mounted transversely, axial mounting reduces heat loss to the stream of hot gas circulating inside the lamp when operating base-up or base-down, resulting in higher efficiency. In addition, the convective flow of gases carries evaporated tungsten upward to be deposited in a location opposite the end of the filament, where it does not intercept much of the emitted light. This results in decreased bulb blackening and increased light output throughout the life of the lamp. Axial mounting also permits use of smaller, more compact bulbs.

Lamp Atmospheres. An incandescent tungsten filament in air would rapidly oxidize and burn up. To prevent such catastrophic failures, the earliest incandescent lamps were evacuated. However, this reduction of pressure permitted rapid evaporation of material from the filament causing (a) accelerated failure of the filament by reduction of its diameter and (b) reduction of light output by deposition of a film of filament material on the inside of the envelope. For these reasons, evacuated tungsten-filament lamps are almost always operated at filament temperatures below approximately 2600K.

Many of the problems encountered in evacuated lamps are eliminated by filling the envelope with an inert gas of low thermal conductivity. Being inert, it does not react with the tungsten filament, and being of low thermal conductivity, it minimizes heat losses from the filament to the envelope. The usual gas pressure is about 80 per cent of atmospheric when the lamp is not operating and rises to about atmospheric when the lamp is operating. This greatly reduces evaporation loss of tungsten from the filament, permitting higher filament operating temperatures and thus higher efficacies.

The heat loss due to the gas fill is proportional to the wire length. At line voltages, low-wattage lamps require long filaments and the gas loss becomes an appreciable fraction of the input power. For this reason lamps below 40 watts are vacuum lamps, as shown in Figure 2.1-1.

The fill gas now used is usually argon, or argon with a small amount of nitrogen added to reduce the possibility of arcing between filament sections or across lead-in wires. The percentage of nitrogen depends on voltage rating, filament operating temperature, and mechanical factors such as filament configuration and the spacing between lead-in wires. Typical percentages of nitrogen range from 0.4% in 6V lamps, through 5% in 120V lamps with coiled-coil filaments, 10% for 230V lamps with fused lead-in wires, and 50% or more for 230V lamps without internal fuses, to 100% in some projection lamps.

Krypton has lower thermal conductivity than argon so that a krypton gas fill reduces heat losses from the filament. Krypton molecules are also heavier than argon molecules resulting in lower filament evaporation and thus increased filament life at given operating temperatures. However, krypton is much more expensive than argon so that it is used only in applications where the increased cost is justified.

In recent years, active gas fills of halogens such as iodine and bromine are being used in lamps to permit higher efficacies without the usual short life associated with high filament temperatures. These tungsten-halogen lamps are discussed in Section 2.2

Filaments. The evacuated lamps made before 1913 had uncoiled tungsten filaments. The use of inert gas fills to retard filament evaporation at higher temperatures and efficacies was not practicable with such filaments because the advantages of higher operating temperatures were nullified by increased heat losses from the filament to the gas. However, it was found that an incandescent filament in an inert gas atmosphere is surrounded by a thin sheath of relatively static gas, and that the portion of filament input power lost to the gas is reduced as the filament diameter is increased. When the filament is formed into a helical coil of small diameter, the sheath surrounds the coil and not the individual filament wire, and the losses are further reduced. The development of the coiled filament made possible the use of inert gas fills by reducing filament heat losses to the gas, thus permitting higher filament temperatures and higher efficacies. The subsequent development of coiled-coil filaments further reduced heat losses and permitted still higher temperatures and efficacies.

The forms and designations of typical filaments for various uses are shown in Figure 2.1-3. Filaments are designated by a letter to indicate the construction (S for straight wire, C for coil, CC for coiled-coil) and an arbitrary number to identify the form. Note that the

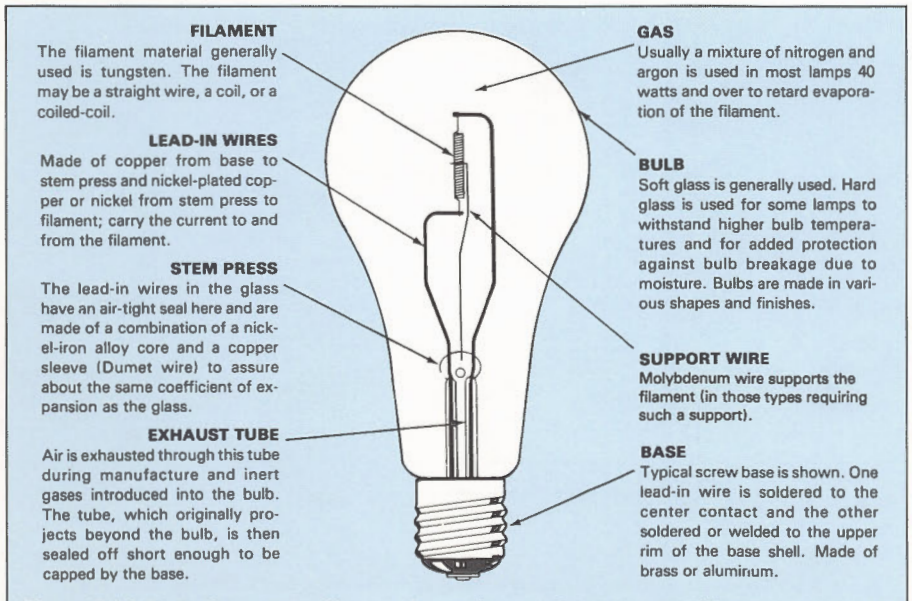
FILAMENT
The filament material generally used is tungsten. The filament may be a straight wire, a coil, or a coiled-coil.
LEAD-IN WIRES
Made of copper from base to stem press and nickel-plated copper or nickel from stem press to filament; carry the current to and from the filament.
STEM PRESS
The lead-in wires in the glass have an air-tight seal here and are made of a combination of a nickel-iron alloy core and a copper sleeve (Dumet wire) to assure about the same coefficient of expansion as the glass.
EXHAUST TUBE
Air is exhausted through this tube during manufacture and inert gases introduced into the bulb. The tube, which originally projects beyond the bulb, is then sealed off short enough to be capped by the base.
GAS
Usually a mixture of nitrogen and argon is used in most lamps 40 watts and over to retard evaporation of the filament.
BULB
Soft glass is generally used. Hard glass is used for some lamps to withstand higher bulb temperatures and for added protection against bulb breakage due to moisture. Bulbs are made in various shapes and finishes.
SUPPORT WIRE
Molybdenum wire supports the filament (in those types requiring such a support).
BASE
Typical screw base is shown. One lead-in wire is soldered to the center contact and the other soldered or welded to the upper rim of the base shell. Made of brass or aluminum.

Figure 2.1-2 Typical tungsten-filament incandescent lamp construction.

axially-mounted filament in Figure 2.1-2 is of the coiled-coil form designated CC8 in Figure 2.1-3. This minimizes convective heat loss due to the hot gases circulating inside the lamp when it is operated in a base-up or base-down position, reduces bulb blackening increasing light output throughout the life of the lamp, and permits use of a smaller, more compact bulb.

Bulb materials for incandescent lamps must be transparent or highly translucent to transmit visible radiation from the filament with minimum loss. These materials should also transmit well in the near infrared because a large portion of the radiation from the filament is in that region of the spectrum, and bulbs made of materials absorbing significant amounts of near-infrared radiation will become excessively hot. Most incandescent lamp bulbs are made of soda lime glass which has a maximum safe operating temperature of 370°C. Lamp bulbs for operation at successively higher temperatures are made of hard borosilicate glass, hard aluminosilicate glass, high-silica glass, or fused silica. The maximum safe operating temperatures of lamps are usually much lower than the softening temperatures of the bulbs, being limited by factors such as the breakdown temperature of the base cement and the melting point of the solder.

Bulb shapes of some typical incandescent lamps are shown in Figure 2.1-4 with their letter designations and names. The letter designations are usually but not always the first letters of the names. Bulb size is designated by a number equal to the maximum bulb diameter in eighths of an inch. Thus a complete reference designation for a bulb will consist of one or more letters and a number.

Bulb shape and size depend on lamp voltage, type of service, gas fill, and the desired operating temperatures of the glass and the base. Most incandescent lamps for general lighting have A bulbs in wattages up to 150W, and PS bulbs in wattages from 150W up.

The designation T covers a wide variety of tubular bulbs, including single-ended and double-ended types, that fit naturally into the optical geometry of many micro/photo/repro graphic systems. Many projection lamps employ T bulbs which permit the close spacings required in compact optical systems. Most tungsten-halogen lamps employ T bulbs, some of which may be placed in reflectorized enclosures such as PAR bulbs.

PAR and R bulbs have internal reflective coatings which, in combination with various filament locations and bulb face finishes, achieve a variety of light distribution patterns ranging from a narrow concentrated beam for spotlighting to a very wide beam for floodlighting.

Finishes and colors are available for a very large number of applications. The most common bulb finishes are clear and frosted. Examples of other finishes are daylight, white, soft-white, soft-pink, and reflective coatings as in silver bowl, PAR, and R lamps. Colors are obtained by using colored glass or by applying coatings to the inside or outside surfaces of the bulbs.

Transparent clear glass bulbs permit use of the filament as a concentrated source of extremely high luminance in projectors and in similar applications. For general lighting purposes, however, it is desirable to diffuse the light from the filament, to reduce glare when lamps are used bare, and to minimize striations and shadows when the lamps are used in lighting fixtures. A common colorless diffusing finish is inside-frosting, an etched finish which partially diffuses the light from the filament while negligibly reducing total light output.

However, inside-frosted lamps still show a hot spot in the vicinity of the filament. White and soft-white lamps have an inside coating of finely divided white silica which provides almost perfect diffusion while reducing total light output by only one or two percent. Daylight lamps use colored glass bulbs which absorb some red and yellow from the light emitted by the filament. The color temperature of the transmitted light is in the range of 3500K to 4000K, which is about halfway between the color temperatures of the light from the filament itself and natural daylight. This increase of color temperature is achieved at a loss of about 35% of total lumen output, so that a 300W daylight lamp has about the same lumen output as a 200W inside-frosted lamp. To compensate for this loss, daylight lamps should have wattage ratings about 50% higher than those of the inside-frosted lamps they replace.

White-bowl lamps have white diffusing coatings inside the half of the bulb opposite the base. When these lamps are operated base-up, about 20% of the light from the filament goes down through the bowl and about 80% of the light goes up to the lighting fixture or ceiling to be reflected down again.

Reflectorized lamps are made in both standard and special bulb shapes by deposition of highly reflective aluminum or silver coatings or dichroic mirrors on portions of the inside surface of the bulb. Because the reflective surfaces are sealed inside the bulbs, they are completely protected from dust, dirt, and oxidation so that their reflectivity remains high throughout the life of the lamp.

Silver-bowl lamps have opaque reflective coatings inside the half of the bulb opposite the base and are used in base-up applications. Since the reflector is opaque, almost 100% of the light from the filament goes up to the lighting fixture or ceiling. These lamps are inside-frosted, so that the bowl appears more white than silver.

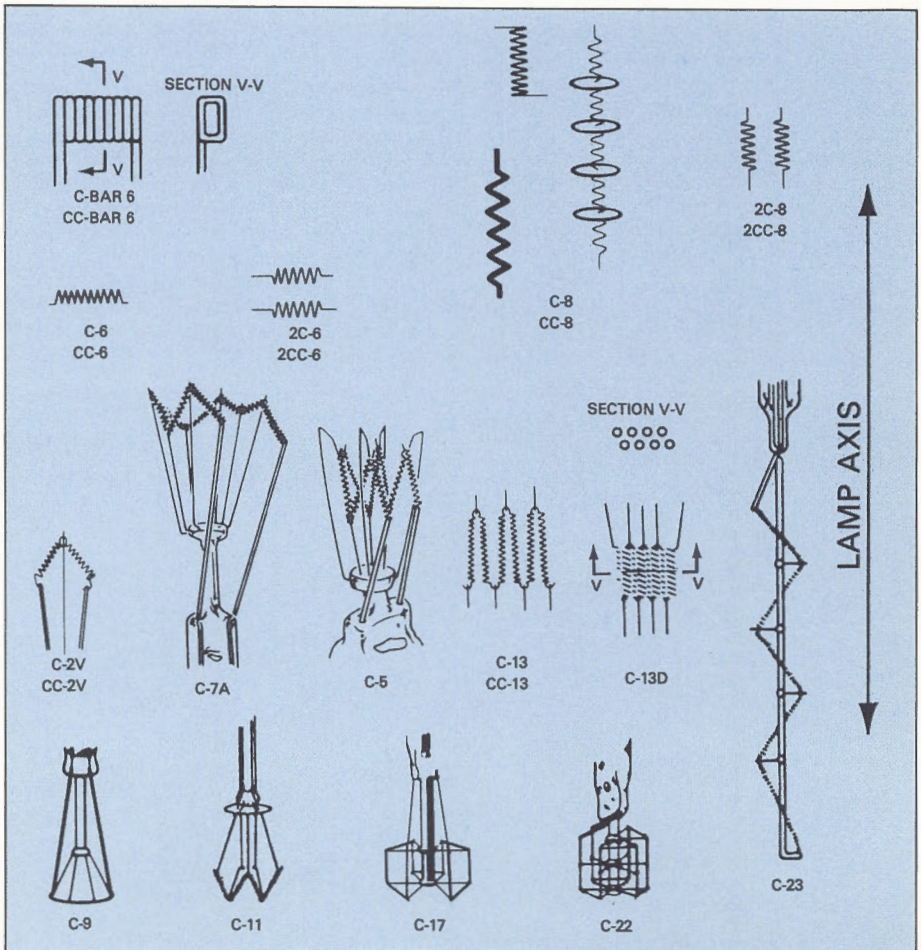

Figure 2.1-3 Typical tungsten filament forms. Not to scale. Note that all filaments are shown oriented with respect to vertical lamp axes.

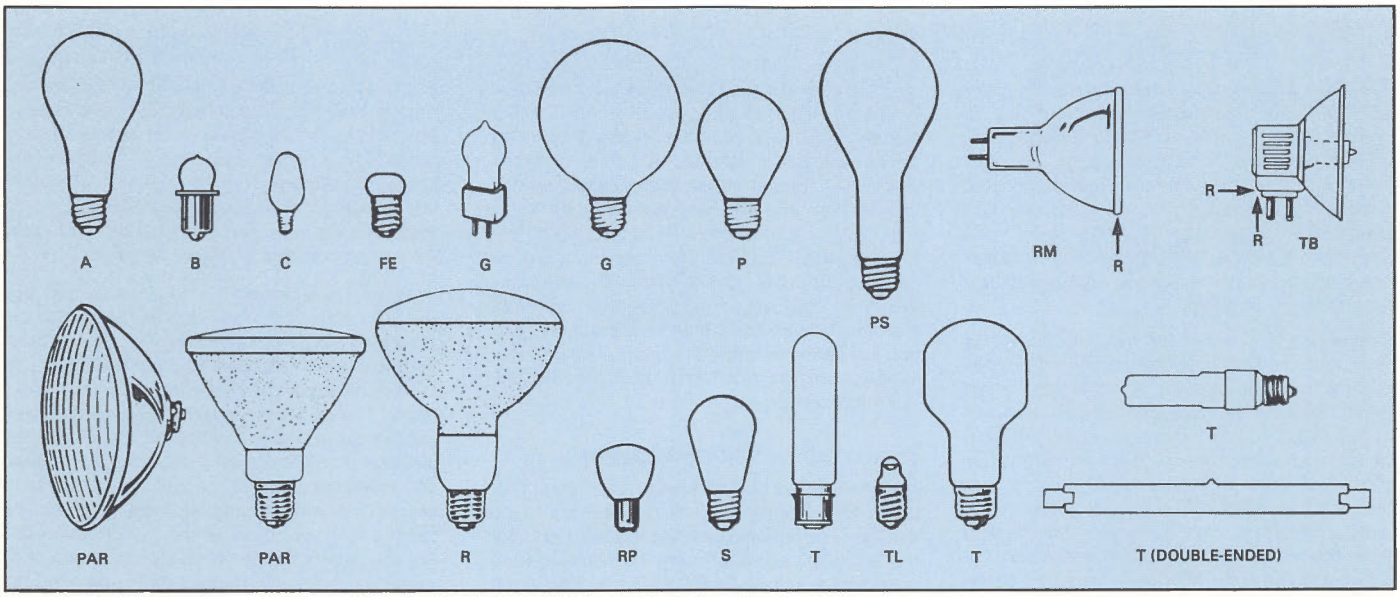

Figure 2.1-4 Typical incandescent lamp bulb shapes. Not to scale. R-location reference.

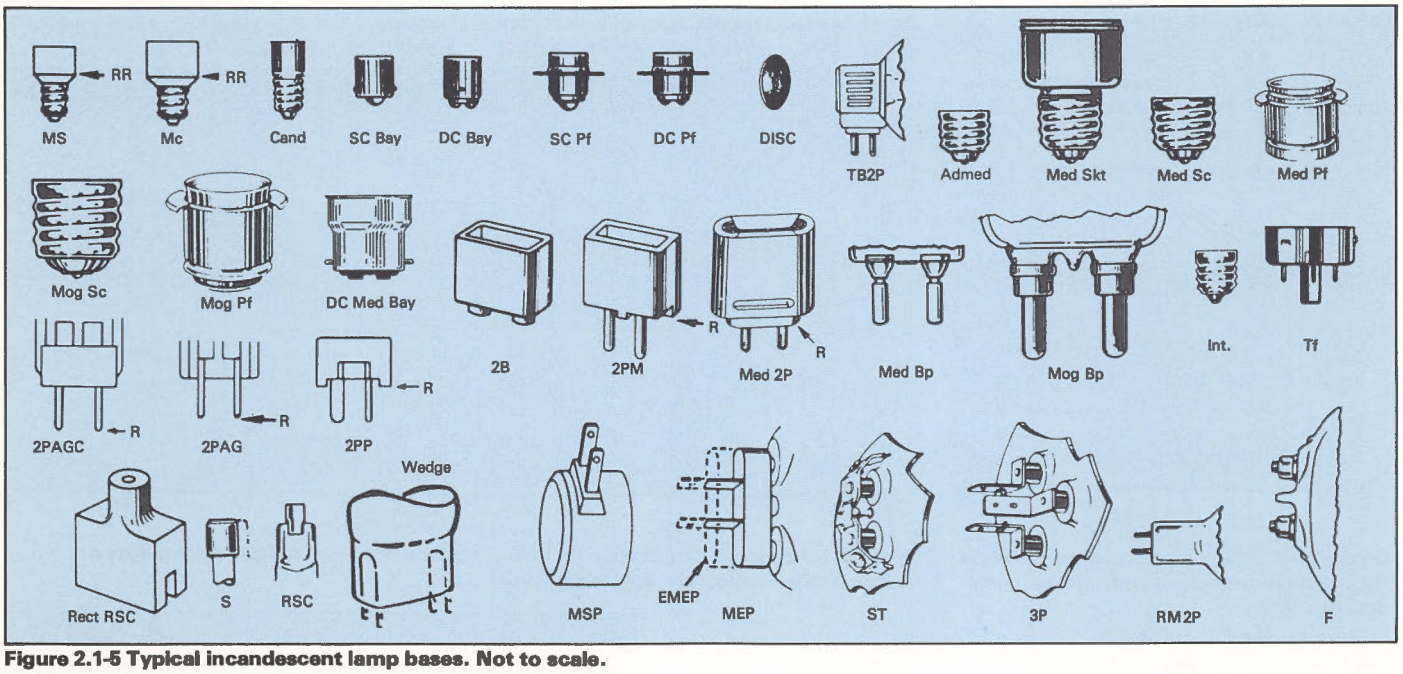

Figure 2.1-5 Typical incandescent lamp bases. Not to scale.

Admed	admedium
Cand	candelabra (E12/15)
DC Bay	double-contact bayonet candelabra
DC Med Bay	double-contact medium bayonet (B22D)
DC Pf	double-contact prefocus candelabra
Disc	lumiline
EMEP	extended mogul end prong
F	ferrule contact
Int.	intermediate (E17/20)
Mc	minican
Med Sc	medium screw (E26/24) also 3 contact (E26D/24)
Med BP	medium bipost (G22)
Med Pf	medium prefocus (P28/25)
Med Skt	medium skirted (E26/50X39), (E26/52X39)
Med 2P	medium two pin (G9.5)
MEP	mogul end prong also extended mogul end prong
Mog Sc	mogul screw (E39/41) also 3 contact (E39D/41)
Mog Bp	mogul bipost (G38)
Mog Pf	mogul prefocus (P40/41)
MS	miniature screw with reference shoulder also Tru-Loc miniature screw
MSP	medium side prong
Rect RSC	rectangular recessed single contact
RM2P	rim mount two pin
RSC	recessed single contact also single contact recessed
S	metal sleeve
SC Bay	single-contact bayonet candelabra (BA15S)
SC Pf	single-contact prefocus (P30S)
ST	screw terminal
TB2P	trubeam two pin
Tf	trufocus (also four pin)
TLMS	see MS
Wedge	wedge
2B	two button
2PAG	two pin all glass
2PAGC	two pin all glass (ceramic cover)
2PM	two pin miniature
2PP	two pin prefocus
3P	three prong

Notes: R indicates special reference point for LCL. (RR at 0.531 inch diameter.)

PAR and R lamps have reflective coatings inside all of the bulb except the face or lens. In some PAR lamps the reflective coating is a dichroic 'cold mirror' which reflects light efficiently through the face while transmitting infrared radiation back through the bulb, thus removing about 65% of the heat from the beam. PAR lamps are available with stained glass lenses and lenses with inside dichroic coatings to provide a variety of colors.

Bases provide means for fastening lamps to their sockets as well as means for conducting current from the sockets to the lamps. Some typical bases for incandescent lamps are shown in Figure 2.1-5. Lamp wattage, operating temperature and type of service are important factors in selection of bases. Most incandescent lamps for general lighting have screw bases with contacts to permit current flow to and from the filament. These bases are usually cemented to the bulbs with cements suited to the rated operating temperatures. Lamps designed for services in which the bases run extremely hot may employ 'mechanical' bases that are clamped to the bulbs.

Prefocus and bipost bases permit precise positioning of lamp filaments in optical systems. The prefocus base has an inner shell which is cemented to the bulb and an outer shell which is positioned with respect to the filament to provide a specified light center length. After the outer shell is positioned, it is soldered to the inner shell. Bipost construction eliminates the typical stem seal and lead assembly shown in Figure 2.1-2 and employs instead a rigid one-piece filament support structure mounted directly to the posts. This configuration transmits the heat and weight of the inner structure directly through the posts to the socket, and not indirectly through the bulb. Sealed-beam lamps employ similar rigid structures for filament support.

Illumination Characteristics

Lumen output and efficacy. The lumen output of an incandescent lamp depends mainly on the filament temperature and the wattage, but the efficacy depends mostly on filament temperatures as shown in Figure 2.1-6. The upper curve in the figure represents the theoretical efficacy of tungsten filaments, and the lower curves represent the efficacies of typical vacuum, gas-filled, and tungsten-halogen incandescent lamps after losses which include: reduction of radiation caused by coiling; end losses; bulb, base, and lead losses; and gas loss. Lamp efficacy as a percentage of theoretical filament efficacy increases from about 65% for 40W lamps to about 80% for lamps of 500W or more, mainly because the percentage gas loss decreases in lamps of higher wattages.

From the foregoing it can be seen that the lumen output of incandescent lamps can be increased almost without limit by increasing their wattage ratings, but the efficacy in lumens per watt is limited by the filament operating temperature. The efficacy of general service incandescent lamps is limited to about 23 lm/W in high-wattage types as shown in Figure 2.1-1. Higher efficacies can be achieved at higher temperatures but with correspondingly reduced life ratings as in projection lamps and photofloods. An efficacy of 35 lm/W repesents a practical upper limit for short-life lamps operating at about 3500K. The lumen outputs and efficacies listed in Figure 2.1-1 are those at rated voltage and can be varied by operation at other voltages as shown in Figure 2.1-14.

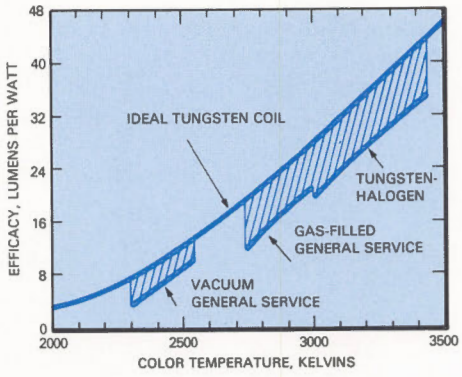

Figure 2.1-6 Efficacy vs color temperature for typical non-halogen and halogen incandescent lamps.

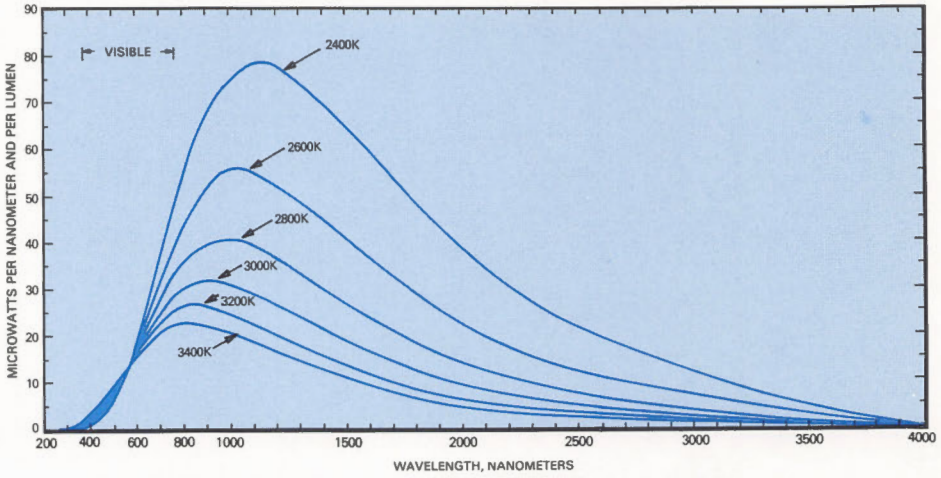

Figure 2.1-7 Spectral distribution of 1 lm of radiant flux from tungsten filaments of various color temperatures. (quartz bulbs)

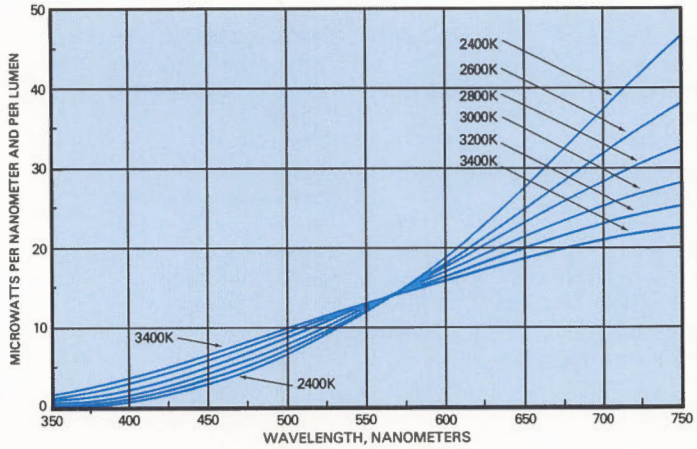

Figure 2.1-8 Spectral distribution in the visible of 1 lumen of radiant flux from tungsten filaments of various color temperatures.

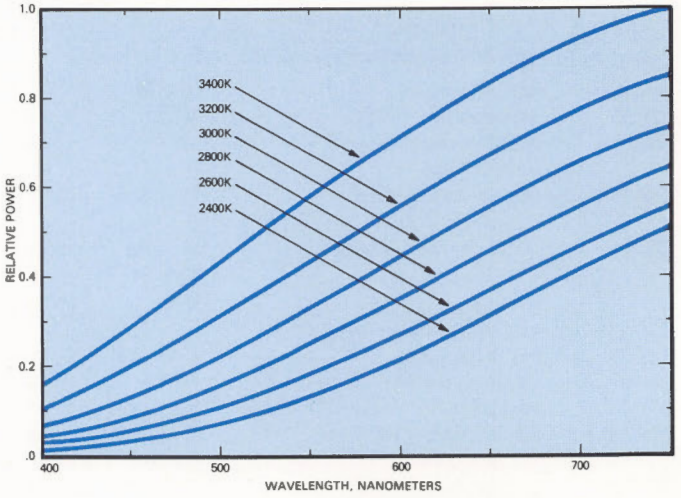

Figure 2.1-9 Relative spectral power distribution in the visible from tungsten filaments of equal wattage but different color temperatures.

Spectral power distribution. The total power radiated by a tungsten filament varies as the fourth power of its absolute temperature. Most of the radiated power is in the infrared, with decreasing percentages in the visible and in the ultraviolet as shown in Figure 2.1-7. Not only does the total radiated power increase with filament temperature but the percentage of the total power radiated in the visible and in the ultraviolet also increases with filament temperature. Thus the efficacy and the color temperature of the filament (which is defined as the absolute temperature of a blackbody having the same chromaticity as the filament) also increase with filament temperature. If the emissivity of tungsten were constant with wavelength and if the filament were at a uniform temperature, the color temperature of a tungsten filament would be the same as the actual absolute temperature; the color temperature is usually within about 100K of the actual absolute temperature of the central part of the filament.

The curves of Figure 2.1-7 may be significantly modified by the spectral transmittance of the bulb material. The spectral transmittance of fused quartz is high over the range from about 200nm to 4000nm, so that it transmits well in the ultraviolet, visible, and infrared. The spectral transmittance of most clear glass is high over the range from about 325nm to 2500nm, so that it transmits well in the visible but absorbs shorter-wavelength ultraviolet radiation and longer-wavelength infrared radiation. Spectral distributions in the visible can be altered by using colored glass bulbs, by applying spectrally selective coatings to the inside or outside of the bulbs, or by using spectrally selective components in the optical systems employing the lamps as light sources.

The curves of Figure 2.1-8 represent expansions of Figure 2.1-7 in the visible. Both figures show the spectral distributions of one lumen of radiant flux from tungsten filaments having different color temperatures.

Figure 2.1-9 covers the visible region like Figure 2.1-8, but shows the relative spectral power distribution from tungsten filaments having equal wattage and different color temperatures. The curves of Figure 2.1-9 show that not only does the total lumen output increase with filament temperature but (since the wattages are equal) the efficacy (lm/W) also increases with filament temperature.

Color temperature of a lamp is an important parameter in many applications. Figure 2.1-10 shows the variation of color temperature with efficacy for typical incandescent lamps (excluding miniature lamps) over a wide range of wattages. The curve is useful in estimating color temperatures from published efficacy ratings or from calculated efficacies if only the lumen output and wattage ratings are published. As stated above, the color temperature of a tungsten-filament lamp is usually within 100K of the filament absolute temperature, and can thus be approximated if the filament temperature is known.

Not only is the color temperature higher for incandescent lamps of greater efficacy, as shown in Figure 2.1-10, but the color tem-

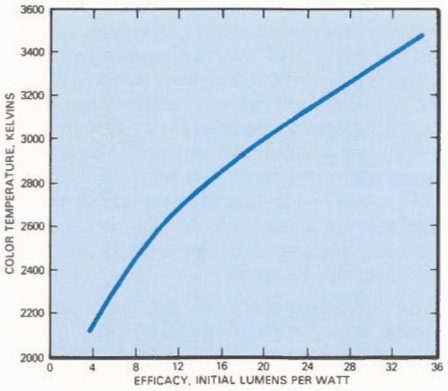

Figure 2.1-10 Color temperature vs. efficacy for typical gas-filled incandescent lamps.

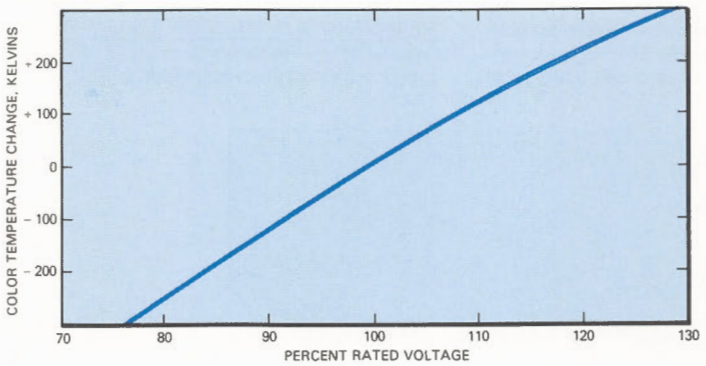

Figure 2.1-11 Variation of color temperature with operating voltage for typical non-halogen and halogen incandescent lamps.

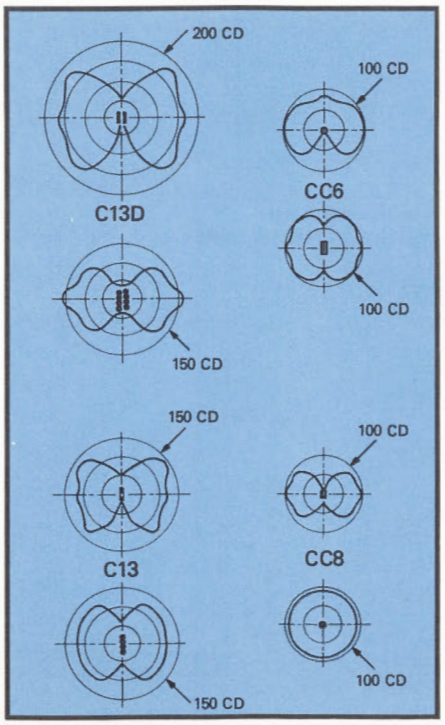

Figure 2.1-12 Polar intensity distributions per 10^3 lumens for typical filament forms.

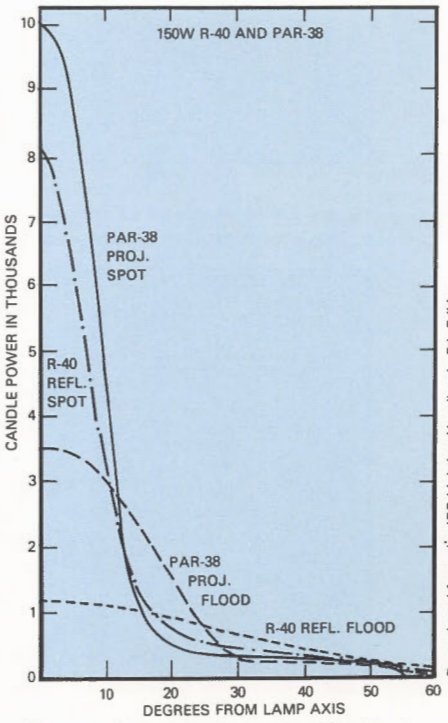

Figure 2.1-13 Polar intensity distributions of typical PAR and R lamps.

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perature of any particular lamp increases with line voltage as shown in Figure 2.1-11.

Polar intensity distribution of incandescent lamps is determined principally by the filament form unless reflectors, etc. are used. Figure 2.1-12 shows intensity distributions for several different typical filament forms.

The intrinsic polar intensity distributions of lamps can be modified for specific applications by reflective and/or refractive elements incorporated as integral parts of the lamp. Reflectorized lamps such as PAR and R types have intensity distributions ranging from wide floodlighting to narrow spotlighting, as shown in Figure 2.1-13.

Operating Characteristics

Effects of operating voltage variations. When incandescent lamps are operated at other than the nominal or rated voltage, the color temperature of the filament varies in accordance with Figure 2.1-11; the resistance, current, wattage, lumen output, and efficacy all vary in accordance with Figure 2.1-14. The curves shown in those figures apply to both conventional non-halogen and halogen incandescent lamps and represent the average of many lamps. The characteristics of individual lamps may deviate increasingly from these curves for variations greater than ±10%. Life of non-halogen incandescent lamps varies in accordance with Figure 2.1-15.

The characteristic curves of Figures 2.1-10, 2.1-13 and 2.1-14 may be represented near rated voltage by the equations given in Figure 2.1-16, where the values at rated voltage are in capital letters and the values at other than rated voltage are in lower case letters. The exponents given were empirically determined from many lamp types and are applicable to lamps having efficacies of about 10 to 25 lumens per watt. Actual exponents may vary from those given for specific lamp types.

The variations of light output, watts, life, efficacy, color temperature, and operating voltage are presented on the Sylvania I-287 Incandescent Lamp Rule* and may be used for rapid and simultaneous calculation of the various quantities.

Filament resistance variations. The hot resistance of tungsten filaments at operating temperatures is much greater than the cold resistance. As shown in Figure 2.1-17, the ratio of hot resistance to cold resistance is about 12 to 14 for vacuum lamps, about 14 to 16 for most gas-filled lamps, and about 18 to 19 for photoflood lamps.

Since the cold resistance of tungsten filaments is about 1/12 to 1/16 the hot resistance, it might be expected that the initial inrush current when rated voltage is aplied to a cold filament would be 12 to 16 times the rated current which flows when the filament heats up to rated temperature. The actual initial inrush current is generally limited to some smaller value by circuit reactance and is a function of the position on the ac wave at which the voltage is applied.

The time for the initial inrush current to decay to the rated current is determined almost entirely by the thermal mass of the filament, and ranges from about 0.05 seconds in 15W lamps to about 0.4 seconds in 1500W lamps.

The inrush current and decay time of incandescent lamp loads is important in the design, selection, and use of circuit breakers, switches, fuses, and other control devices. For typical values of these parameters, see Figure 2.1-1.

*Available on request from GTE Sylvania Lighting Center, Danvers, Mass. 01923.

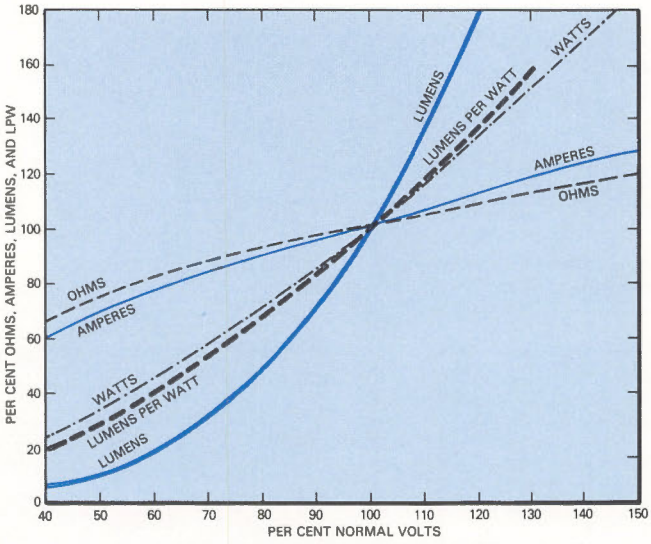


Figure 2.1-14 Variation of characteristics with operating voltage for typical nonhalogen and halogen incandescent lamps.

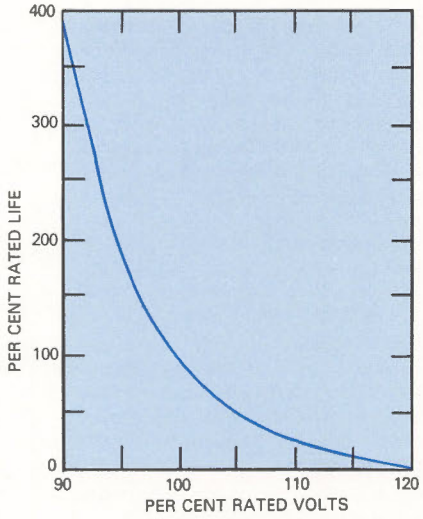


Figure 2.1-15 Life vs operating voltage for typical non-halogen incandescent lamps.

$$\frac{\text{lumens}}{\text{LUMENS}} = \left(\frac{\text{volts}}{\text{VOLTS}}\right)^{3.4}$$

$$\frac{\text{lumens/watt}}{\text{LUMENS/WATT}} = \left(\frac{\text{volts}}{\text{VOLTS}}\right)^{1.9}$$

$$\frac{\text{watts}}{\text{WATTS}} = \left(\frac{\text{volts}}{\text{VOLTS}}\right)^{1.6}$$

$$\frac{\text{ohms}}{\text{OHMS}} = \left(\frac{\text{volts}}{\text{VOLTS}}\right)^{0.4}$$

$$\frac{\text{amperes}}{\text{AMPERES}} = \left(\frac{\text{volts}}{\text{VOLTS}}\right)^{0.6}$$

$$\frac{\text{life}}{\text{LIFE}} = \left(\frac{\text{VOLTS}}{\text{volts}}\right)^{13}$$

$$\frac{\text{color temperature, °K}}{\text{COLOR TEMPERATURE, °K}} = \left(\frac{\text{volts}}{\text{VOLTS}}\right)^{0.42}$$

Figure 2.1-16 Variations of operating characteristics with voltage for large incandescent lamps.

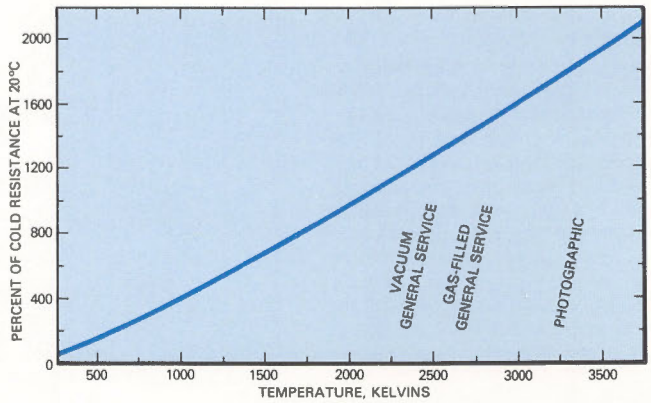


Figure 2.1-17 Variation of tungsten filament resistance with temperature.

Dimming considerations. Light output of incandescent lamps is a function of the root-mean-square (r.m.s.) value of the applied voltage. Dimming is easily accomplished over large ranges by varying the amplitude of voltage applied to the lamp, or by varying the duty cycle of the voltage applied to the lamp. The amplitude may be varied by means of variable resistors (rheostats) or variable autotransformers. The duty cycle, which is the percentage of each ac period that current is permitted to flow, may be varied by means of thyratrons, saturable reactors, magnetic amplifiers, or silicon controlled rectifiers. Note that dimmers must be capable of handling the large change in filament resistance that results from temperature variations.

Lamps designed for low voltage may be operated on high voltage circuits using transformers or series impedance to reduce the voltage. Variable duty cycle transformation should not be used. It may still apply the peak system voltage to the lamp. This can cause arcing since it exceeds the design value of the lamp.

Depreciation during life. Figure 2.1-18 shows changes in characteristics during life for typical incandescent lamps operated at (a) rated voltage, or (b) rated current. Reductions in lumen output and lumens per watt are called 'depreciation' of those characteristics.

The major factors in depreciation during life of incandescent lamps are evaporation of tungsten from the filament and bulb blackening. Evaporation of tungsten decreases the filament wire diameter and increases its resistance. For lamps operating at constant voltage the increased resistance causes a reduction in amperes, watts, lumens, and lumens/watt. For lamps operating at constant current the increased resistance causes increased voltage, wattage, and (initially) lumens. Low-current lamps operated at constant current may have very small depreciation, or even a slight increase of lumen output during life. High-current lamps operated at constant current usually have bulb blackening so rapid that it offsets the increased lumen output.

Bulb blackening, caused by deposition of evaporated tungsten particles on the inner surface of the bulb, reduces lumen output and efficacy by reducing bulb transmittance. In vacuum lamps the blackening is fairly uniform, but in gas-filled lamps the evaporated tungsten particles are carried by convection to the upper part of the bulb. Blackening therefore occurs mainly on the bowls of lamps operated base down and on the necks of lamps operated base up. Since most of the light in the neck region is usually intercepted by the base, blackening of the neck does not greatly reduce lumen output so that lamps (especially those with axial coiled-coil filaments) operated base up maintain their lumen output and efficacy better than lamps operated base down.

The 'water cycle' is another factor in lamp depreciation. The glass and metal inside the lamp may contain absorbed hydrogen and oxygen which are liberated during operation. The water vapor which is formed contacts the filament and forms tungsten oxide which is deposited on the cooler bulb. Here, the tungsten oxide is reduced by the hydrogen leaving metallic tungsten on the bulb wall while the water vapor is again free to repeat the process. Also, in the presence of minute quantities of water, tungsten is removed from the hottest filament area and deposited, through the gas phase, to nearby cooler areas of the filament. This causes the hot area to be hotter and leads to early lamp failure. Water-cycle effects are greatly reduced by the use of active materials called 'getters' which combine with and absorb oxygen or water vapor that may be liberated during initial operation.

Life expectancy (mortality) curves. Lamp life is defined as the arithmetic mean life based on a large sample life test perfomed under laboratory conditions of controlled voltage, etc. Figure 2.1-19 shows a range of typical mortality curves giving the expected percentage of survivors as a function of burning time. Note that (a) approximately 50% will fail prior to rated life, (b) small samples are not likely to give the same average value, and (c) the distribution of failures in actual use will probably differ from the standardized results due to voltage variation, environmental conditions, etc.

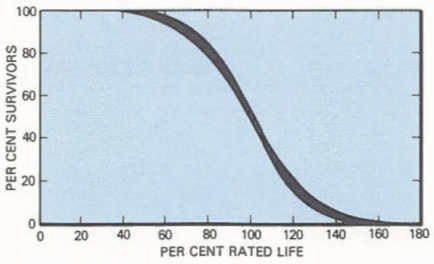


Figure 2.1-19 Life expectancy (mortality) curves for typical non-halogen and halogen incandescent lamps.

Factors affecting lamp life. Lamp failure can result from a variety of causes such as filament evaporation, recrystallization, notching, etc. These processes can be slowed (e.g., varying evaporation by change of filament temperature or gas fill) but cannot be entirely eliminated.

The filament is not at an absolutely uniform temperature, and evaporation is greater at hot spots. Reduction of wire size at these points exacerbates the condition. Normal failure usually occurs at such spots, often triggered by the in-rush current at turn-on. During operation, filaments recrystallize making them fragile and more susceptible to mechanical shock and vibration failures.

Notching is the formation of sharp irregularities at the filament surface during operating life. The effect is more pronounced on d.c. than on a.c. voltage. For small diameter filament wire (less than about 0.001 inch), especially as used in miniature lamps, the notches may be an appreciable fraction of the wire diameter. This causes hot spots and localized reduction in strength leading to early lamp failure. Thus, lamps with very fine filament wire operated on d.c. may have a life of one-half or less than that obtained on a.c. operation.

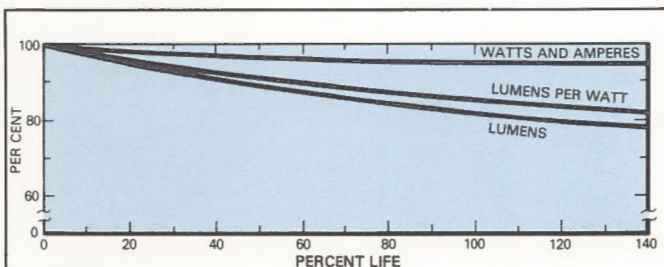
Tungsten filaments are more fragile at room temperature than at elevated temperatures, particularly when there is some embrittlement due to crystallization as the filament ages with use. As the filament cools from its operating temperature on turn-off, it passes through a 250°C to 350°C 'brittle-ductile transition region' at temperatures below which it is much more liable to breakage. Various additives (e.g., thorium and rhenium) in manufacture tend to minimize this effect, but lamp life can be prolonged in operation by reducing the number of on-off cycles. Where extreme reliability is required, 'keep-alive' power equal to about 1% of operating power can be applied to the filament to warm it even during the off condition as a technique extending lamp life.

Operating voltage has an enormous effect on lamp life, which varies inversely with about the thirteenth power of the voltage, as illustrated in Figure 2.1-15.

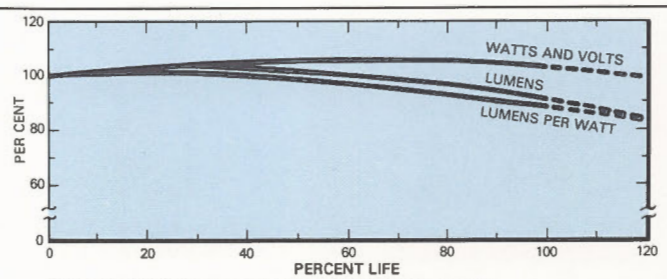
Tungsten Filament Lamps for M/P/R Application

Photoflood lamps

Photoflood lamps are designed to operate at very high temperatures, achieving high total light outputs and efficacies up to 35 lm/W with rated lives in the range of 4 to 20 hours. The ratings range from 250 to 1000W. The various types include:



(a) typical 200W lamp operated at rated voltage



(b) typical 20A lamp operated at rated current.

Figure 2.1-18 Changes in operating characteristics during life for typical incandescent lamps.

PAR types with various beam spreads and color temperatures of 3200K to 3450K.

PAR types with daylight dichroic filter coatings giving color temperatures of 5000K.

Conventional inside-frosted and integral-reflector types, with color temperatures of 3200K to 3450K.

Conventional types with daylight-blue-glass bulbs, with color temperatures of about 5000K.

Photo-Enlarger Lamps

There are two general types of enlargers, the condenser type which requires a nearly point source, and the diffuser type which may employ either a point source of a distributed source. Incandescent lamps with diffuse white bulbs, in ratings from 75 to 500W, with color temperatures of 2950K to 3200K, and rated lives of 20 to 100 hours are designed for diffuser-type enlargers.

Projection Lamps

These lamps for use in slide, filmstrip, and motion-picture projectors have compact filaments, high filament operating temperatures, high efficacies and short lives. Lamps without internal reflectors are used in projection systems employing a reflector behind the lamp and a condenser lens in front of the lamp to collect the light and direct it to the film aperture; an objective lens projects the image of the film aperture on to the screen. A relatively small portion of the light from the lamp is collected so that the efficiency of this system is quite limited.

Old-style projection lamps were designed for refraction optical systems employing external reflectors and condenser lenses. They are available in ratings of 50 to 1200W, with color temperatures of 2850K to 3325K, and in a variety of bases. Although included in the old-style listing, the CXL single contact candelabra prefocus base lamp has an internal reflector and the DFR Focus-Lok lamp has a proximity reflector. Old-style lamps are primarily for replacement purposes, although they may be used in low-cost projection systems.

Tru-Focus projection lamps employ keyed snap-in bases and specially-designed sockets for automatic alignment of the filament in the projector optical system. They are available in soft glass bulbs with power ratings from 75 to 750W and in hard glass bulbs with power ratings from 400 to 1200W. Many types are rated for operation at 120V, but some 12V, 24V, and 230V types are available. Typical life ratings are 10 to 50 hours. A few types have life ratings of 200 to 500 hours. Some Tru-Focus lamps have small internal 'proximity' reflectors located immediately behind the filament which collect light from the rear of the filament and reflect it through the filament area to the film aperture. This results in higher efficiency and a brighter projected image. The reflector, which is hermetically sealed against dirt and oxidation, is replaced each time the lamp is replaced, and thus maintains high reflectivity.

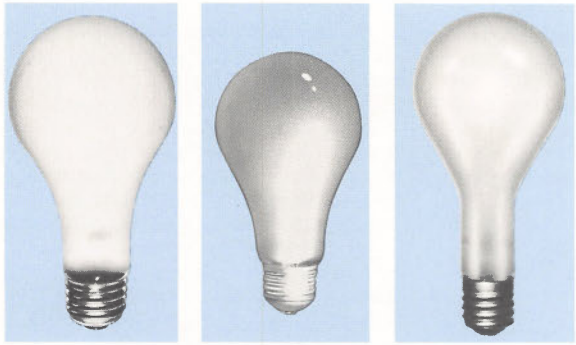


Figure 2.1-20 Conventional types of photoflood lamps.

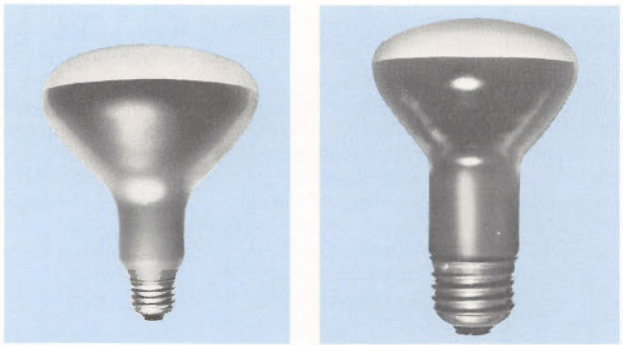


Figure 2.1-21. PAR photoflood lamp.

Figure 2.1-22 Typical photo-enlarger lamps.

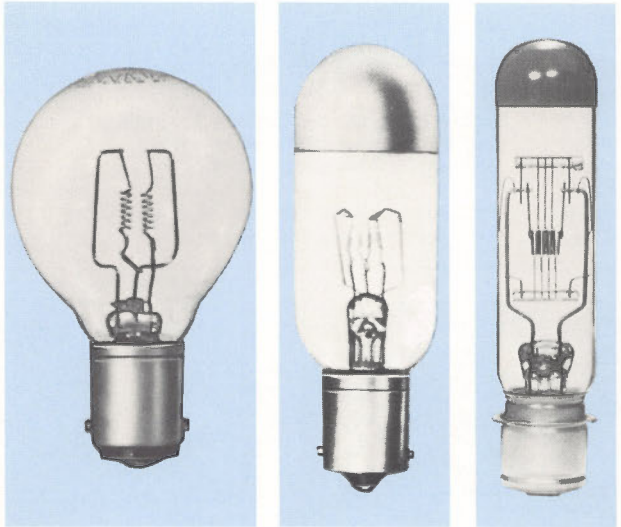


Figure 2.1-23 Typical old-style projection lamps.

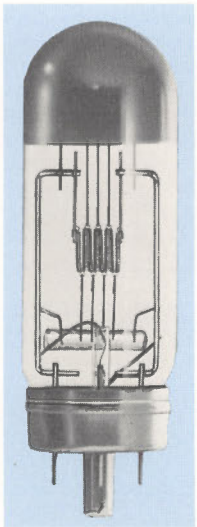


Figure 2.1-24. Typical Tru-Focus projection lamps.

Tru-Flector projection lamps have snap-in bases for easy, automatic alignment, and internal ellipsoidal reflectors that collect almost a full hemisphere of the filament light output and focus it directly on the film aperture. This system eliminates external reflectors and condensing lenses, and produces much greater intensity at the film aperture. The resulting image projected by the objective lens can be significantly brighter while using less wattage than a lamp in a conventional optical system with condensing lenses. They are available in power ratings from 35W to 250W and voltage ratings from 6V to 120V. Typical life ratings are 10 to 25 hours; the 35W/6V type DKN has a rated life of 500 hours.

For non-halogen projection lamps under normal operating conditions, the maximum bulb wall temperature is 300°C for soft glass lamps and 450°C for hard glass lamps. This is measured at a point on the bulb wall directly opposite the coil center using an infrared pyrometer. Maximum base temperatures are 200°C for soft glass lamps and 300°C for hard glass lamps. These are measured with a thermocouple in contact with the glass under the base.

Tungsten-halogen projection lamps are discussed in Section 2.2.

Exciter Lamps

Exciter lamps are low wattage lamps used to illuminate the sound track on motion-picture film. These are highly stable precision lamps designed to minimize optically generated noise in the audio system.

Studio Lamps

These lamps are designed for use in a variety of theatre, television, and photographic lighting luminaires such as fresnel lens and ellipsoidal reflector spotlights, parabolic beam projectors, scoops and other floodlights, etc. They are almost always designed for color temperatures of 3000K and above. Wattage ranges from one to two hundred watts up to 10,000 watts. Except for floodlights, non-halogen lamps used in such equipment almost always have C13 or C13D filaments. Bulbs are usually of T or G shape, and bases are of the more precise alignment types such as bipost or prefocus.

In recent years, tungsten-halogen lamps frequently are substituted for non-halogen lamps due to the advantages at high color temperatures. Most modern equipment is designed exclusively for tungsten-halogen lamps to take advantage of the smaller bulbs, the availability of compact CC8 filaments, etc.

2.2 Tungsten-Halogen Lamps

The tungsten-halogen lamp is similar to the conventional non-halogen incandescent lamp in that it employs a tungsten filament in a gas-filled, light-transmitting envelope and emits the same type of light. The major differences are that a trace of halogen vapor (e.g., iodine or bromine) is added to the inert fill gas, the gas pressure and bulb temperature are much higher than in non-halogen lamps, and the bulb is made of fused quartz (silica, SiO_2), high-silica glass or aluminosilicate 'hard' glass to withstand the high operating pressures and temperatures. The first of these lamps employed fused quartz bulbs and iodine vapor and were thus called 'quartz-iodine' lamps. Since other high-temperature bulb materials and other halogens may be employed, the more generic term 'tungsten-halogen' is now used.

Tungsten-halogen lamps operate in a 'halogen regenerative cycle' which maintains constant light output and color temperature throughout the life of the lamp. The halogen cycle permits the use of more compact bulbs than those of conventional tungsten-filament lamps of equal ratings, and also permits either increasing lamp life to approximately twice that of conventional tungsten filament lamps having comparable wattage and color temperature or increasing color temperatures and lumen outputs to values significantly above those of conventional tungsten filament lamps having comparable life and wattage.

The Halogen Cycle

In conventional gas-filled tungsten-filament lamps, tungsten molecules evaporate from the hot filament, are carried by convection currents of the inert fill gas to the relatively cool inner surface of the bulb, and are deposited to form a thin film which gradually increases in thickness during the life of the lamp. These phenomena cause depreciation of lumen output and efficacy in two ways. First, deposition of the evaporated tungsten on the bulb wall builds up a film of increasing opacity which absorbs increasing portions of the light produced by the filament and thus reduces the total light output. Second, evaporation of tungsten from the filament reduces the filament wire diameter, increasing the resistance and thus (at constant voltage) decreasing the amperes, wattage, lumens, lumens per watt, and color temperature.

In tungsten-halogen lamps, the effects described above are reduced or retarded by the regenerative action of the halogen cycle, which operates by virtue of the temperature gradient between the filament and the bulb. As a general concept:

a. The filament, fill gas, and bulb are initially at some low temperature (e.g., ambient, for a cold start).

b. When power is applied, the filament rapidly rises to its operating temperature (2800K to 3400K depending on application), heating the fill gas and the bulb. The bulb wall rises to an operating temperature of 400°C to 1000°C, and the fill gas rises to temperatures ranging from that at the filament to that at the bulb wall. This temperature gradient causes convection currents in the fill gas.

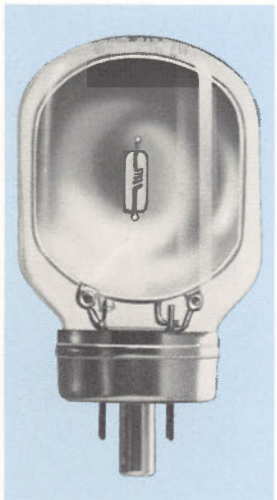


Figure 2.1-25. Typical Tru-Flector projection lamps.

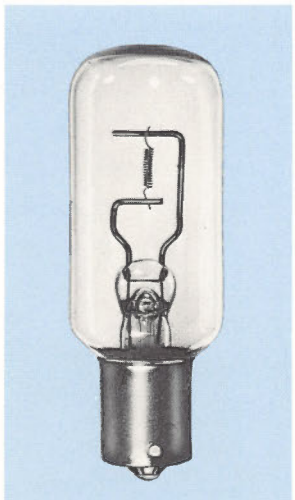


Figure 2.1-26 Typical exciter lamp.

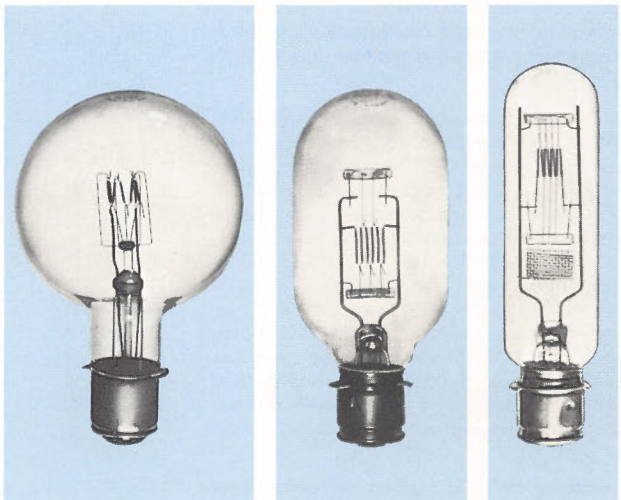


Figure 2.1-27 Typical studio lamps.

c. As the bulb wall rises above temperatures in the range 200°C to 250°C (depending on nature and amount of halogen vapor), the halogen cycle begins to operate. Tungsten molecules evaporated from the filament combine with the halogen vapor to form a tungsten halide (e.g., tungsten iodide or tungsten bromide). The halide does not condense on the hot wall of the bulb but is circulated by convection back to the region of the filament.

d. At the filament where the temperature exceeds 2500°C, the tungsten halide dissociates, the tungsten is deposited on the filament, and

e. The free halogen vapor is recirculated to continue the regenerative cycle. This cycle thus keeps the bulb wall clean by preventing deposition of tungsten and results in much higher lumen maintenance over the life of the lamp than that obtained for conventional tungsten-filament lamps.

Physical Characteristics

Typical Construction Features

Bulb shapes and sizes. To maintain the high temperatures and pressures required for operation of the halogen cycle, tungsten-halogen lamp bulbs are significantly smaller and have generally thicker walls than the bulbs of non-halogen incandescent lamps of comparable wattage. As shown in Figure 2.2-1, the bulb shapes are usually tubular (T) and sometimes globular (G). The bulbs are generally designated by letter(s) for the shape and a number giving the maximum diameter in eighths of an inch, as for other lamps. Note that this designation system does not include the bulb length, nor does it tell whether the bulb is single-ended or double-ended.

Some lamps employ small tungsten-halogen 'capsules' sealed inside outer bulbs or jackets (e.g., PAR-Q lamps) or mounted in open-front reflectors (e.g., Tru-Beam and Tru-Beam Rim-Mount lamps). Figure 2.2-2 shows construction details of PAR-Q lamps, which have small double-ended tungsten-halogen capsules sealed inside reflectorized PAR outer bulbs. These lamps generally have designations derived from the PAR bulbs.

Bulb materials must be capable of withstanding high operating temperatures (generally between 400°C and 1000°C) and pressures. Fused quartz (silica, SiO_2), with a melting point of 1650°C, is usually used because it can easily operate at wall temperatures which may be as high as 1100°C. For wall operating temperatures up to about 600°C, high-silica glass (96% silica glass, e.g., Vycor®) is sometimes used, especially for short-life photographic lamps. Aluminosilicate 'hard' glass has recently been introduced for use in low-voltage tungsten-halogen lamps rated at 50W or less, with wall operating temperatures less than about 400°C.

Atmospheres of tungsten-halogen lamps comprise an inert gas with about 0.1% to 1.0% of a halogen vapor added. The inert gas may be krypton, argon, or nitrogen, or a mixture (e.g., krypton/argon or argon/nitrogen) having the highest atomic weight consistent with cost as well as arc-resistance suitable to the lamp design and the operating voltage. The halogen vapor may be pure iodine (I_2) or a compound of iodine (e.g., CH_3I) or of bromine (e.g., HBr, CH_3Br, or CH_2Br_2). Iodine is still used in long-life lamps for general illumination but bromine is now used in most tungsten-halogen lamps, especially those for photographic and reprographic applications. The minimum bulb wall temperature for operation of the halogen cycle is about 200°C for bromine which is significantly lower than the 250°C for iodine. Bromine is also colorless while iodine has a very slight absorption in the yellow-green.

Unlike conventional tungsten-filament lamps which operate with an internal gas pressure of about one atmosphere, most tungsten-halogen lamps operate with an internal gas pressure of several atmospheres to reduce the rate of tungsten evaporation. The combined effects of higher pressure and the halogen cycle give halogen lamps much longer life than that of comparable non-halogen incandescent lamps operating at the same filament temperatures. Conversely, when the two types are designed for equal life, halogen lamps will operate at higher filament temperatures with consequently greater luminance and efficacy.

Filaments are generally coiled or coiled-coil tungsten filaments of the more compact forms (e.g., C6, C8, C2V, C13, C13D, and C BAR 6) shown in Figure 2.1-3. These forms are identified by the same two-part designation as for non-halogen incandescent lamps. Segmented-filament lamps employ several such filaments in series, with spacings controlled to give desired light distributions.

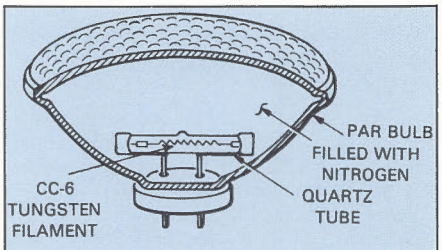


Figure 2.2-2 PAR-Q tungsten-halogen lamp construction.

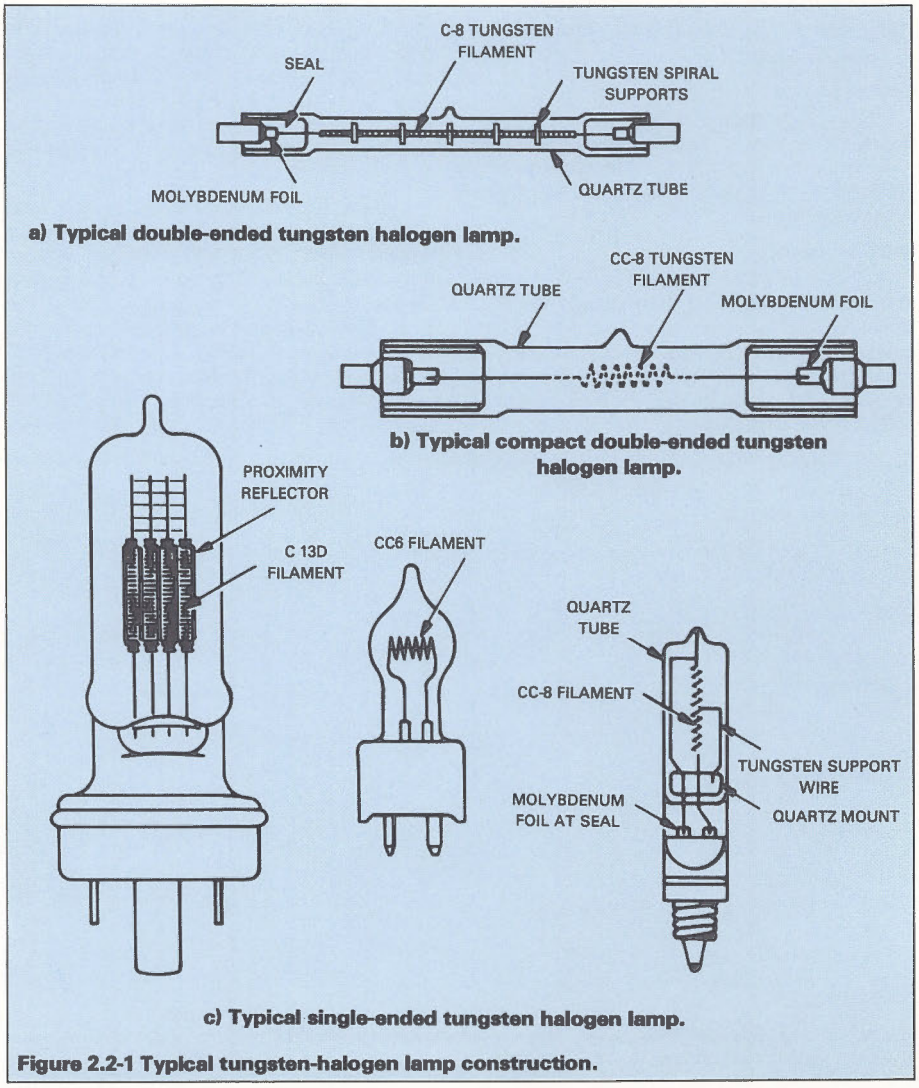


Figure 2.2-1 Typical tungsten-halogen lamp construction.

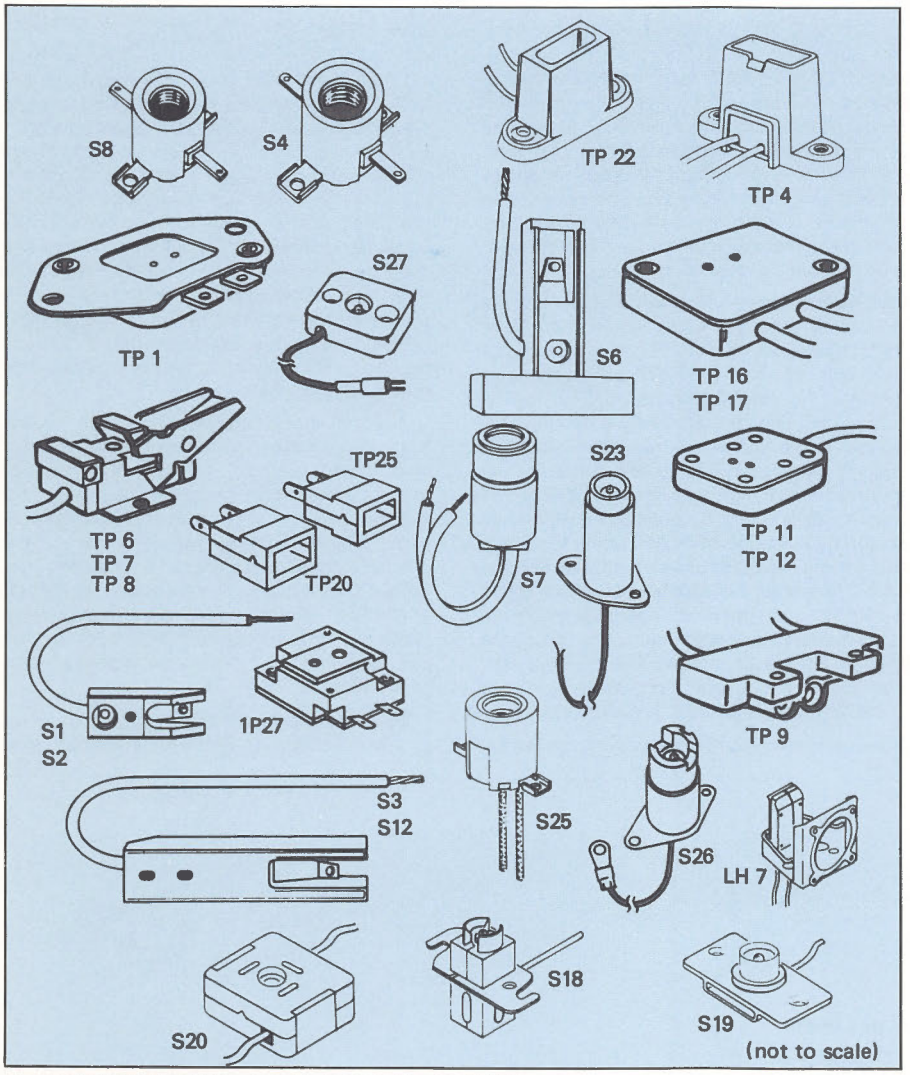


Figure 2.2-3 Typical tungsten-halogen lamp sockets.

	ORDERING ABBREVIATION	BASE (6)	MAXIMUM WATTAGE	MAXIMUM CURRENT	MAXIMUM TEMPERATURE
DOUBLE-ENDED LAMPS	S1/12	RSC ONLY	650	6 amp	250°C (3)
	S2/12	RSC ONLY	1500	10 amp (2)	350°C (3)
	S3/12	RECT. RSC & RSC	1500	10 amp	350°C (3)
	S6/12	RECT. RSC & RSC	1500	10 amp (2)	350°C (3)
	S12/12	RECT. RSC & RSC	2000	10 amp	350°C (3)
	S18	RSC	2000	15 amp	350°C (7,9)
	S19	RSC	2000	15 amp	350°C (7,9)
	S23	RSC	3000	15 amp	350°C (3)
	S26	RSC	3000	15 amp	350°C (3)
	S27	RSC	3000	15 amp	350°C (3)
SINGLE-ENDED LAMPS	S4	MC	1000	8.5 amp	300°C (4)
	S7/12	MC	1000	8.5 amp	300°C (4)
	S8	MS	75 (1)	8.5 amp	300°C (4)
	S20	EMEP	1500	10 amp	200°C (5)
	S25	MC	1000	8.5 amp	300°C (4)
	TP1	2PM	750	10 amp	300°C
	TP4	MED. 2P	1000	10 amp	200°C (5, 10)
	TP6	2PP	750	10 amp	200°C (5)
	TP7 & 8	2PP	1200	10 amp	200°C (5)
	TP9	2PAG & 2PAGC	750	10 amp	200°C (5)
	TP11 & 12	2PM	750	10 amp	150°C (5)
	TP16 (12)	2PAG & 2PAGC	750	10 amp	150°C (5)
	TP17 (12)	2PAG & 2PAGC	750	10 amp	150°C (5)
	TP22	MED. 2P	1000	10 amp	200°C (5)
	LH (8)	RM2P	750	10 amp	150°C (5)
	TP20	WEDGE	75	10 amp	225°C (11)
	TP25	WEDGE	25	6 amp	225°C (11)
	TP27	2PP	750	10 amp	200°C (5)

Figure 2.2-4 Ratings of typical tungsten-halogen lamp sockets.

Seals. As illustrated in Figure 2.2-1 the electrical current leads of tungsten-halogen lamps with fused quartz bulbs are generally flat molybdenum ribbons that connect the filament leads to the base contacts. These ribbons are sealed into the bulb material at the points where they pass through the bulb. The temperature of these seals has a significant effect on lamp life because temperatures exceeding 350°C will cause rapid oxidation of the molybdenum ribbons and early lamp failure. Since oxidation is a function of both time and temperature, lamps with short life ratings may have maximum seal temperature ratings up to 450°C.

The contrasting requirements that the bulb wall must be at high temperatures in order for the halogen cycle to operate and that the seal temperatures not exceed about 350°C for rated life, can be simultaneously satisfied only by conducting heat away from the seals and/or shielding the base area from direct filament radiation. The thermal properties of the lamp bases and sockets thus become important factors in the operation of tungsten-halogen lamps. Special lamps with thermocouples incorporated into the seal area are used to test equipment designs that operate near the critical seal temperature limits.

Bases generally used on tungsten-halogen lamps are shown in Figure 2.1-5. They are identified by letter designations, some of which are arbitrary, and some of which are abbreviations (e.g., the recessed-single-contact base is designated RSC).

Maximum overall length (M.O.L.) and light center length (L.C.L.) are two important base-referenced lamp dimensions. The M.O.L. of single-ended lamps is measured from the top of the bulb to the bottom of the base; the M.O.L. of double-ended lamps is measured between the outer ends of the two bases. The L.C.L. of single-ended lamps is measured from the center of the filament to the bottom of the base for screw bases, to the top of the base pins for bayonet bases, to the top of the fins for prefocus bases, to the shoulder of the posts for mogul bipost bases, and to the bottom of the bulb (base end) for medium bipost bases. Some bases have special reference points, which are shown in Figure 2.1-5.

Sockets for tungsten-halogen lamps must maintain high mechanical pressure and good electrical contact with the lamp bases despite high operating temperatures to prevent arcing, pitting, and corrosion that cause increased contact resistance and consequent localized heating. The sockets must also provide good thermal contact with the bases, to conduct heat away from the seals. The sockets shown in Figure 2.2-3 have been specifically designed to

1. WITH SPECIAL APPLICATIONS UP TO 350 WATTS.
2. HIGHER CURRENT RATING CAN BE ATTAINED WITH FORCED COOLING.
3. AT REAR OF CONTACT BUTTON.
4. AT REAR OF CENTRAL CONTACT BUTTON.
5. AT LEAD WIRE JUNCTION.
6. SEE FIGURE 2.1-5
7. AT CONTACT BALL.
8. LH-5, BASE UNIT; LH-7, ADDS EJECTOR; LH-9 ADDS EJECTOR AND MOUNTING FOOT.
9. ONE S18 AND ONE S19 ARE USED FOR EACH LAMP.
10. TP22 IS A PREFERRED REPLACEMENT FOR TP4.
11. AT CONTACT.
12. TP16 AND TP17 REPLACE THE OBSOLETE TP2 AND TP3 RESPECTIVELY.

meet the stringent requirments for proper operation of tungsten-halogen lamps. The maximum temperatures listed in Figure 2.2-4 for each type of socket must be maintained by ventilation and even heat-sinking if necessary.

Types of Tungsten-Halogen Lamps

Double-ended tungsten-halogen lamps in ratings of 500W and 1500W were the first commercially available type. They were made as shown in Figures 2.2-1a and 2.2-5, with T3 bulbs and C8 filaments. This double-ended type, which is widely used for general lighting applications, now includes other bulb sizes and ratings. Certain of these lamps must be operated within 4° of the horizontal to prevent bulb blackening.

Compact double-ended tungsten-halogen lamps, shown in Figures 2.2-1b and 2.2-6, have shorter filaments, shorter bulbs, and often larger-diameter (up to T-8) bulbs than the double-ended lamps shown in Figure 2.2-1a. The short filament permits precise location in optical systems and operation in any position. This series includes ratings from 45W to 2000W.

Single-ended tungsten-halogen lamps, shown in Figures 2.2-1c and 2.2-7, include types in ratings from 50W to 10,000W. The single-ended construction and compact filaments provide efficient light distribution and permit the design of compact fixtures for spot, flood and general lighting, and optical device applications. These lamps can be operated in any position. Internal proximity reflectors are used in some of these lamps for projection systems and optical devices.

PAR-Q tungsten-halogen lamps are made by sealing compact double-ended tungsten-halogen capsules inside PAR reflectorized bulbs filled with an inert gas such as nitrogen, as shown in Figures 2.2-2 and 2.2-8. This configuration combines the advantages of tungsten-halogen lamps (longer life, higher efficacy, and better lumen maintainance) with those of PAR lamps (constant high reflectance and choice of beam spreads). The inert gas prevents failures caused by oxidation of molybdenum seal leads at the higher temperatures of enclosed lamps. PAR-Q lamps are available in ratings from 500W to 1000W, with light distributions ranging from narrow spot to very wide flood. The faceplates of some PAR-Q lamps have dichroic multilayer filter coatings that raise the color temperature to 5000K for photographic applications.

Tru-Beam and Rim-Mount reflector lamps are prefocused reflective condenser types made by mounting single-ended tungsten-halogen capsules coaxially within open front reflectors as shown in Figure 2.2-9. A principal advantage of these reflector lamps is that the filament is optically aligned and optimized with respect to the reflector in a system representative of the intended application. This provides better and more consistent performance in the final device than mechanical alignment of the filament by means of the lamp base and socket. Tru-Beam lamps are positioned by means of their two-pin bases and Rim-Mount lamps are positioned by means of their reflector rims.

The reflectors can be made with shapes (e.g., ellipsoidal or paraboloidal), finishes (e.g., smooth or 'peened'), and reflective coatings (e.g., dichroic 'cold mirror' or aluminized) to suit the requirements of many types of applications. Ellipsoidal reflectors can eliminate the need for condensing lenses in projection systems. Other reflector shapes permit the design of hybrid reflective-refractive condensing systems. The reflectors can be smooth, or they may be peened to provide a controlled amount of diffusion.

Dichroic cold-mirror coatings on the reflectors can be used to concentrate light towards

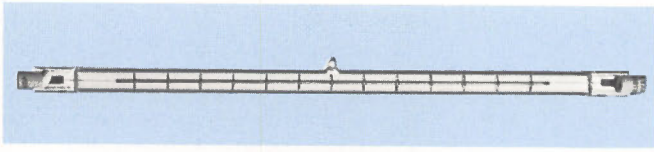


Figure 2.2-5 Typical double-ended tungsten-halogen lamp.

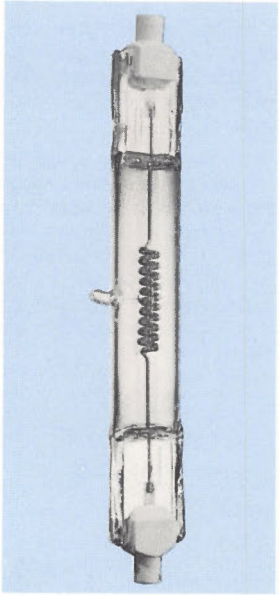


Figure 2.2-6 Typical compact double-ended tungsten-halogen lamp.

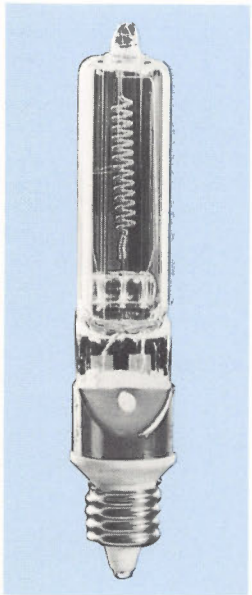


Figure 2.2-7 Typical single-ended tungsten-halogen lamps.

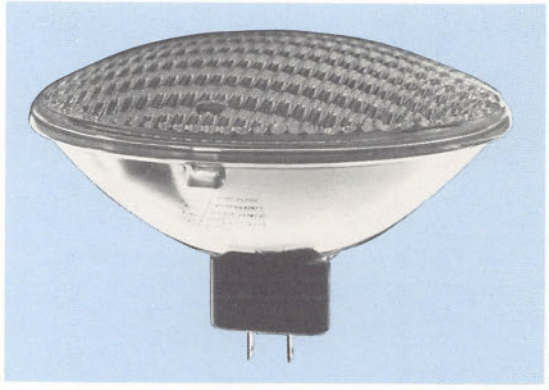


Figure 2.2-8 Typical PAR-Q tungsten-halogen lamp.

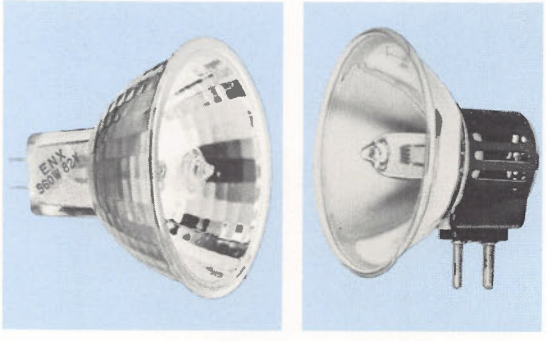


Figure 2.2-9 Reflective-condenser tungsten-halogen projector lamps.

the front while permitting a significant portion of the infrared to pass through the reflector towards the rear, thus greatly reducing heating effects in the forward direction (e.g., at film apertures or gates) and often eliminating the need for lossy absorptive heat filters. Reflective condensing systems with cold-mirror coatings are generally more efficient than refractive condensing systems with absorptive heat filters because cold-mirror coatings can have reflectances exceeding 90% in the visible, while absorptive heat filters generally have transmittances as low as 70% and the transmittance is further reduced by losses in the condensing lenses. The efficiency of the reflective system is often so much greater than that of the refractive system that it produces comparable light output with lamps of lower wattage.

Fully-reflecting aluminum coatings are used where it is desired to concentrate all of the lamp output (including the infrared) in the forward direction (e.g., for non-contact heating applications such as soldering or brazing).

Most of the presently available lamps in this group have been designed for use in optical projection systems, especially where the light is to be concentrated at a film gate or aperture. Although each existing type has been designed to match the characteristics of a particular optical device or system, it is often possible to adapt an existing type to another application.

Hard-glass tungsten-halogen lamps are single-ended lamps with aluminosilicate hard-glass bulbs that permit the use of less expensive materials and construction techniques as shown in Figure 2.2-10. For example, conventional wire electrical leads replace the molybdenum foil pressed-seal leads required for fused quartz bulbs. The materials and techniques used impose temperature limitations which restrict wattages to a maximum of about 100 watts. The lamps are used in luminaires and optical devices having conventional base-socket relations. They are also available prefocused in reflectors as shown in Figure 2.2-11. Due to the low powers involved, these reflectors are usually made of aluminized plastic rather than of dichroic-mirror-coated glass.

Segmented-filament lamps as illustrated in Figure 2.2-12 are long tungsten-halogen lamps in which several filament segments are separated by non-radiating conductors. These long lamps may be used within a few inches of a long narrow target area for photocopying, fusing, and similar applications. Segmented filaments are used to overcome a major disadvantage of continuous filaments, which is that the illumination along the target drops significantly near the ends of the lamp in comparison to the central value. In segmented-filament lamps, the illumination along the target can be made fairly uniform by using several filament sections along the lamp axis and properly spacing them for a specific target length and distance from the lamp. By this technique it also is possible to increase the illumination at the ends above that at the center, which is a requirement of some optical systems. These lamps are generally of high wattage (e.g., 1500W for 12 inch lighted length).

Tungsten-halogen lamps for studio, theatre, and television lighting are available in ratings from 100W to 10,000W. Figure 2.2-13 shows a typical lamp in this group. Some of these lamps are designed to be direct replacements for non-halogen incandescent lamps in studio, theatre, and television lighting equipment such as fresnel spotlights, scoop type fixtures, ellipsoidal reflector spotlights, etc.

Illumination Characteristics

Lumen output and efficacy. For equal filament temperatures, the efficacy of a tungsten-halogen lamp is approximately that of a non-halogen incandescent lamp initially (see Figure 2.1-6). For equal lives and wattages, halogen lamps operate at higher filament temperatures, higher lumen outputs, and higher efficacies. Iodine absorbs slightly in the yellow-green and bromine is colorless; consequently tungsten-iodine lamps have a percent or so less total lumen output than tungsten-bromine lamps.

Spectral power distribution and color temperature. The spectral power distribution and color temperature relations of non-halogen incandescent lamps (discussed in Section 2.1) also apply to halogen lamps. Since the spectral power distribution of halogen lamps is essentially the same as that of non-halogen lamps operating at the same filament temperatures, the curves of Figures 2.1-7, 2.1-8, and 2.1-9 apply to halogen lamps. Because halogen lamps operate at higher filament temperatures than non-halogen incandescent lamps having equal life and wattage ratings, the halogen lamps have generally higher color temperatures. The common range of color temperatures for halogen lamps is 2900K to 3400K. Typical standard long-life halogen lamps operate at a color temperature of about 3000K and halogen lamps designed for studio, theatre, and television lighting operate at somewhat higher color temperatures, often about 3200K.

Polar intensity distribution. As in non-halogen lamps, the polar intensity distribution for halogen lamps is usually determined more by the filament form than by the bulb and base. The intrinsic polar intensity distributions of tubular halogen lamps may be modified by

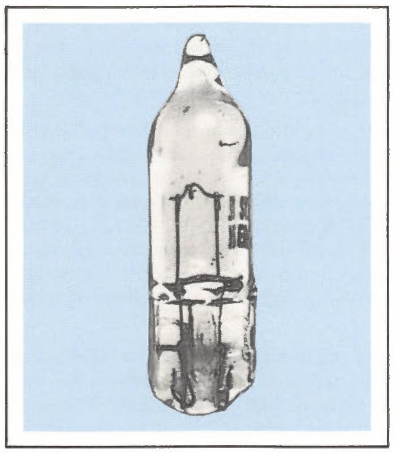


Figure 2.2-10 Hard-glass tungsten-halogen lamp.

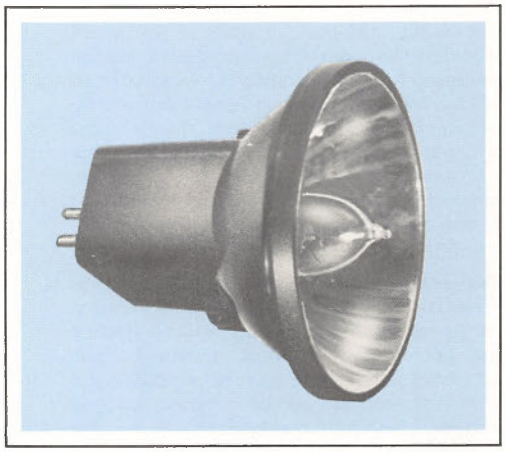


Figure 2.2-11 Hard-glass tungsten-halogen lamp in plastic reflector.

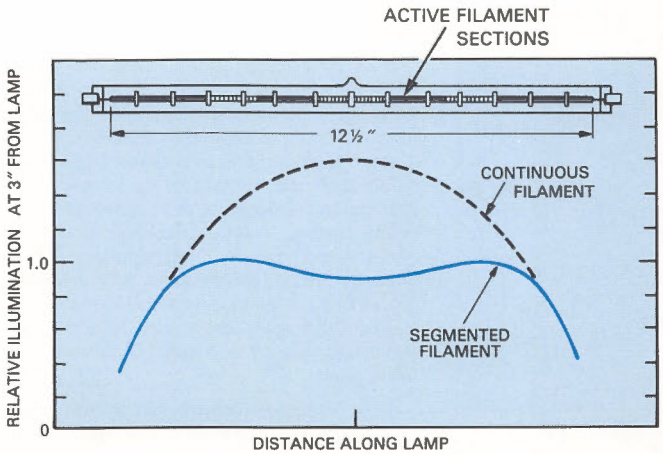


Figure 2.2-12 Segmented-filament tungsten-halogen lamp.

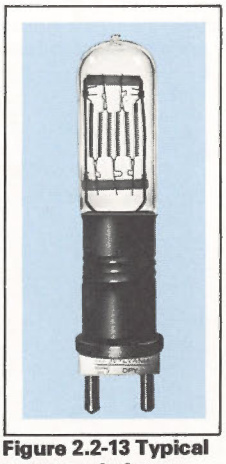


Figure 2.2-13 Typical tungsten-halogen lamps for studio, theatre and television lighting.

mounting them in reflectorized PAR jackets to achieve floodlighting or spotligting distributions, or in reflectorized Rim-Mount or Tru-Beam forms to illuminate film apertures in projectors.

Operating Characteristics

Effects of operating voltage variations. The color temperature of halogen lamps varies with voltage as shown in Figure 2.1-11. For typical 120V lamps, the color temperature changes about 10K per volt. The filament resistance, current, wattage, lumen output, and efficacy all vary as shown in Figure 2.1-14. The exponential equations of Figure 2.1-16 or the Sylvania I-287 Incandescent Lamp Rule may also be used to calculate the variations of characteristics with voltage for halogen lamps.

Dimming considerations. Halogen lamps can usually be dimmed over large ranges. At some point in the dimming process, the bulb wall temperature may fall too low and the halogen cycle may cease to function. However, the tungsten evaporation rate at dimmed filament temperatures also decreases so that bulb wall blackening does not usually occur. Where blackening does occur, usually in equipment employing forced cooling, such blackening can be cleaned up by operating the lamp at rated voltage for a short time and prevented entirely by employing luminaires that maintain the lamps at non-blackening temperatures over the full dimming range. Theatrical luminaires employing halogen lamps are usually designed to operate at temperatures above the blackening range.

Depreciation during life. The halogen cycle maintains the color temperature of halogen lamps nearly constant throughout life and slows the depreciation of most operating characteristics. This can be seen by comparing the lumen depreciation curves of typical halogen and non-halogen incandescent lamps for photographic applications as shown in Figure 2.2-14.

Life expectancy curves. The mortality curve of Figure 2.1-19 applies to halogen as well as non-halogen incandescent lamps.

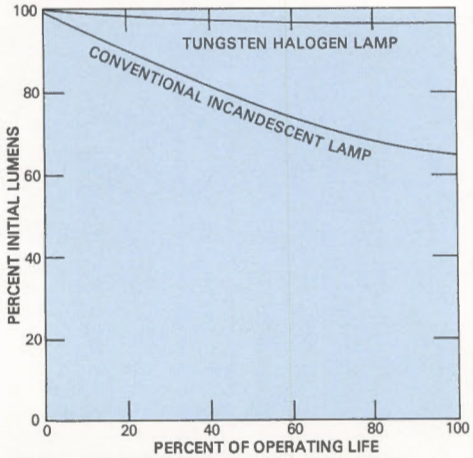


Figure 2.2-14 Comparison of lumen depreciation for halogen and non-halogen incandescent lamps.

Factors affecting life. The life of non-halogen incandescent lamps is mainly dependent on the rate of evaporation of the tungsten filament, and thus on filament temperature. The life of tungsten-halogen lamps is affected not only by the rate of filament evaporation, but also by factors such as gas pressure at operating temperature, bulb and seal temperatures, amount and nature of halogen compound in the fill, etc. Theoretically the lamp would last indefinitely if the tungsten were redeposited on the filament in a manner exactly matching the evaporation loss rate, i.e., mainly on the higher temperature portions. Actually, however, the tungsten is redeposited mainly on intermediate-temperature regions of the filament, and does not compensate exactly for evaporation loss. Moreover, in some lamp types in which a high rate of deposition of tungsten on the bulb wall requires a very active halogen cycle to prevent bulb blackening, halogen erosion of the lowest-temperature parts of the filament may result in thinner sections which eventually break. As a result, the life of halogen lamps, especially at other than rated operating conditions, cannot be predicted as accurately as that of non-halogen incandescent lamps. For example, at lower than rated voltages, the theoretically longer lamp life based on filament evaporation may not be reached because erosion of the filament at the ends of the coil, and other factors peculiar to halogen lamps may cause earlier failure.

Due to the interaction of many parameters, tungsten-halogen lamps invariably give best overall performance at rated design voltage. Whenever possible, the principal operating condition should be at rated voltage. Derating voltage may improve some factor such as life, but not to the extent possible for a lamp specifically designed for that operating condition.

Lamp seal temperatures above 350°C cause rapid oxidation of the molybdenum foil leads that carry current through the seals. This would result in the seal failing before the filament in a long-life lamp. Since oxidation is a function of both time and temperature, some lamps with short design lives may be operated with seal temperatures as high as 450°C. Because tungsten-halogen lamp bulbs must be operated hot but without exceeding the seal temperature limits, socket design, luminaire design, and cooling are important considerations.

Bulb cleanliness affects lamp life because many substances, including oils from the skin, will cause fused quartz to 'devitrify' (i.e., revert to a high-thermal-expansion crystalline form) at normal bulb operating temperatures. Early lamp failure then occurs because the stresses resulting from the presence of this crystalline material cause crazing, eventual leakage, and subsequent filament failure. Tungsten-halogen lamps therefore should be handled only with clean gloves or with the original packing materials. If tungsten-halogen lamps are handled, they should be cleaned with suitable solvent before being used.

Most tungsten-halogen lamps for general lighting applications are designed for 2000-hour life at rated voltage. The life at other than rated voltage cannot be predicted as accurately as for conventional incandescent lamps. The life of some but not all tungsten-halogen lamps may be extended at reduced operating voltages. However, reduced voltages do not generally decrease life below rated values, so that these lamps can usually be operated successfully on dimmers.

2.3 Photoflash Lamps

There are two types of lamps used to produce high-intensity light flashes of short duration for photographic purposes. Xenon gas discharge lamps, commonly called 'electronic flash' or 'strobe' lamps or 'flashtubes', which are capable of producing hundreds of thousands of flashes, are discussed in Section 6.1. The disposable lamps, usually called 'photoflash lamps' or 'flashbulbs', and sometimes referred to as 'chemical flash lamps', are discussed in this section. The principal parameters characterizing flash lamps are quantity of light, color temperature, time from ignition to peak output, and duration of output.

Physical Characteristics

Basic Construction Features

Photoflash lamps are incandescent lamps which employ a chemical reaction, namely the rapid oxidation of a combustible metallic foil (e.g., aluminum, hafnium, or zirconium) in an atmosphere of pure oxygen to generate a brief high-intensity flash of light. Although the foil and the oxygen are both present, the rapid oxidation that constitutes combustion does not occur until the foil is ignited by a primer. Once initiated, combustion of the foil proceeds rapidly and irreversibly until the foil is completely consumed. The primer that initiates the combustion of the foil may be ignited electrically as in Figure 2.3-1 or mechanically as in Figure 2.3-2. In either case, the amount of energy required to ignite the primer is only a very small fraction of the energy in the light flash, which is chemical energy released by combustion of the metallic foil inside the lamp.

Low-resistance, electrically-ignited photoflash lamps have leads through which current is fed to heat a filament to incandescence in times on the order of a millisecond. The incandescent filament ignites a primer material initiating combustion of the metallic foil in the oxygen atmosphere.

Low resistance photoflash lamps rated for 3-45V operation (e.g. AG1, Press 25, Flash cube, etc.) may be operated from dry cells or batteries having voltages from 3Vdc to 45Vdc. The current drawn is usually about 3A, but for such a short time that the total energy required for ignition is typically about 10 millijoules (10mJ). This amount of energy is so small that the average dry cell or battery used to supply it may last a year or more even after hundreds of flashes.

Low-resistance photoflash lamps rated for 3-125V operation (e.g. types 2 and 3) may be operated from dry cells or batteries in the same manner as the lamps with 3-45V ratings, and they may also be operated from 115-125V ac

lines. These lamps have internal fuses to prevent power line fuses from blowing on the high surge or inrush currents drawn by filaments of such low resistance when connected across ac lines.

High-resistance electrically-ignited photoflash lamps such as those used in the Flip Flash and Super 10 Flip Flash, require 2000V (minimum) pulses of approximately one microsecond in duration to heat directly a small portion of the primer to ignition temperatures by means of an internal spark. Such lamps have no filament and consequently have a very high lead-to-lead resistance before flashing. The ignition energy requirement of about 50 microjoules (50μJ) is so low that those lamps may be fired by a pulse from a small piezoelectric element in the camera that is struck by a shutter-actuated hammer. Thus, although Flip Flash lamps are electrically ignited, batteries are not required for this function. The piezoelectric element lasts indefinitely, and can be struck many thousands of times without deterioration or reduction of its electrical output. The element is so reliable that Flip Flash cameras have no means for disabling the hammer, which thus strikes the element every time the shutter is actuated, whether or not the Flip Flash is used.

The only present example of the mechanically-ignited photoflash lamp, the Magicube, has a metal primer tube projecting downward from the lamp base. The primer tube contains an internal rod that is coated with primer material. When a spring-driven striker in the Magicube is released by a shutter-actuated release pin in the camera, the striker dents the primer tube, compressing the primer material against the internal rod and igniting the primer material. The ignited primer material flares up through the open upper end of the primer tube into the interior of the lamp, initiating combustion of the metallic foil in the oxygen atmosphere. Since Magicubes are mechanically ignited, batteries are not required for this function.

Types by Configuration

The single photoflash lamps of the types listed in Figure 2.3-3a and shown in Figure 2.3-4 are all electrically-ignited low resistance types constructed generally in accordance with Figure 2.3-1a. The bulbs are of soft glass that is coated with a tough thin film of lacquer for protection against breaking or shattering. Either clear or blue lacquer may be used depending on the desired color temperature. Blue lamps of a given type are indicated by the suffix B (e.g., AG1B); clear lamps have no suffix (e.g., AG1). Either clear or blue lamps can be used with black-and-white (B/W) films, but blue lamps are for use with daylight-type color films.

Multiple photoflash lamp arrays of the types listed in Figure 2.3-3b are examples of assemblies containing four or more subminiature flashbulbs similar to the miniature AG1B. Each lamp is positioned precisely in front of a metallized plastic reflector so that no external reflector is required. Each assembly is contained within a transparent plastic housing that protects the flashbulbs from breakage, provides a flashguard for every shot, and protects users' hands from the heat of fired flashbulbs. Each type provides means for automatically firing the lamps in sequence and for indicating those lamps that have been fired. Because either the flashbulbs or the plastic housings are blue, these multiple photoflash lamps can be used with both B/W and daylight type color films. The various types of multiple photoflash lamps are described below. Note that each type of multiple photoflash unit requires a specially-designed camera or flash adapter with a matching socket and mechanisms and/or circuits for firing and sequencing.

Flashcubes and HI-Power Flashcubes are transparent plastic cubes containing four low-resistance electrically-ignited flashbulbs, one behind each vertical face of the cube. A positive-latching base permits instant attachment to, or removal from, cameras or adapters having matching sockets. Ignition of the front lamp is initiated by and synchronized with the camera shutter; operation of the film advance mechanism after each picture indexes the cube 90°, rotating a new lamp to the front. Four pictures can be taken as fast as the shutter actuation-film advance cycle can be performed. The battery and other components required to ignite the lamp fit easily inside even a compact 126 camera.

Magicubes (Figure 2.3-5a) are similar to Flashcubes and are indexed in the same manner, but the flashbulbs are mechanically ignited by a shutter-actuated release pin in the camera, which projects up through the socket and base.

Flash Bars (Figure 2.3-5b) are clear plastic packages containing two back-to-back linear arrays of five electrically-ignited and electrically-sequenced low-resistance subminiature lamps. When Flash Bars are used on Polaroid SX-70 and similar cameras, the electrical power required for ignition is supplied by the battery contained in the film pack. After the five front lamps are fired in sequence by successive shutter actuations, the flash bar is unplugged, reversed end for end, and replugged into the socket on the camera. The five new lamps thus brought to the front may then be sequentially fired. The electrical sequencing method employed automatically fires the next new front flashbulb even though the Flash Bar may have been removed from and replaced on the camera after the previous flashbulb was fired. This eliminates lost exposures and wasted flashbulbs.

Flip Flash units are double-ended flat packages containing eight electrically-ignited and electrically-sequenced high-resistance flashbulbs in two planar arrays of four each. When the contact tab or edge connector at one end (the 'bottom') is plugged into the matching linear socket on the camera, internal switches in the Flip Flash connect the four flashbulbs at the other end (the 'top') one after

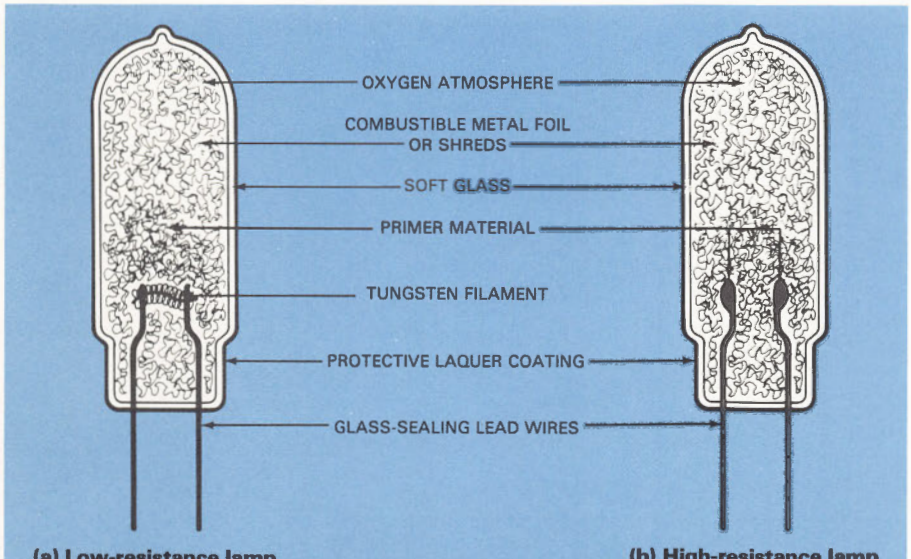


Figure 2.3-1 Electrically-ignited photoflash lamps.

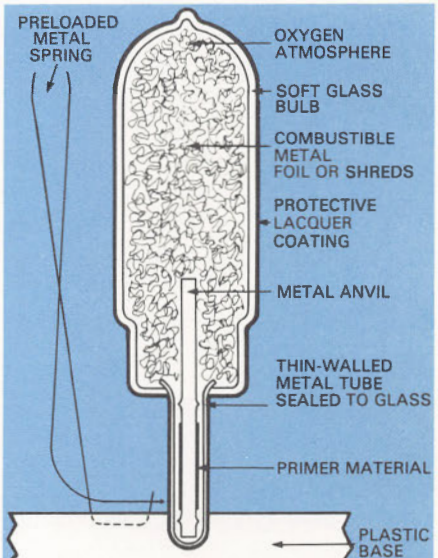


Figure 2.3-2 Mechanically-ignited photoflash lamps.

TYPE	CLASS	APPROXIMATE TOTAL LIGHT OUTPUT, LM-SEC (NOTE 2)	APPROXIMATE TIME TO PEAK, MSEC	APPROXIMATE DURATION AT HALF-PEAK, MSEC	APPROXIMATE PEAK LUMENS	IGNITION VOLTAGE RANGE, VOLTS	APPROXIMATE COLOR TEMPERATURE °K	BULB SHAPE	BULB DIAMETER, INCHES	MAXIMUM OVERALL LENGTH, INCHES	BASE	SHUTTER SYNCHRONIZATION
AG1B	MF	5,300	12	15	250,000	3-45	5500	T3-3/4	15/32	1-5/16	NOTE 1	X TO 1/30;ALL M SPEEDS
AG1	MF	7,200	12	15	450,000	3-45	3800	T3-3/4	15/32	1-5/16	NOTE 1	X TO 1/30;ALL M SPEEDS
PRESS 40	M	33,000	20	17	1,900,000	3-45	3800	A15	1-7/8	4-1/16	MED. SCREW	X TO 1/30;ALL M SPEEDS
2B	M	33,500	20	18	2,000,000	3-125	5500	A19	2-3/8	4-3/4	MED. SCREW	ALL M SPEEDS
3	S	110,000	30	18	6,000,000	3-125	3800	A23	2-7/8	5-15/16	MED. SCREW	S TO 1/30
FP26B	FP	9,800	—	24	270,000	3-45	5500	B12	1-1/2	2-5/8	S.C.BAYONET	ALL FP SPEEDS
FF33	SPECIAL	140,000	—	1750	11,000	4.5-45	3800	A23	2-7/8	5-15/16	MED. SCREW	FLOODFLASH;55,000 LM-SEC FOR 2.5 SEC

NOTES: 1. GLASS GROOVE BASE 2. MEASURED OVER 4π STERADIAN'S

(a) Typical single photoflash lamps

TYPE	CLASS	APPROXIMATE TOTAL LIGHT OUTPUT BEAM CANDLE-POWER-SEC (NOTE 3)	APPROXIMATE TIME TO PEAK, MSEC	APPROXIMATE DURATION AT HALF PEAK, MSEC	APPROXIMATE PEAK BEAM CANDLE-POWER	IGNITION VOLTAGE RANGE, VOLTS	APPROXIMATE COLOR TEMPERATURE °K	SHAPE	FACE WIDTH, INCHES	MAXIMUM OVERALL LENGTH, INCHES	BASE	SHUTTER SYNCHRONIZATION
MAGICUBE	MF	2,000	7	10	150,000	MECH.IGN.	5500	CUBE	1-7/32	1-19/32	PLASTIC	X, F TO 1/60
FLASHCUBE	MF	2,000	13	15	130,000	3-45	5500	CUBE	1-1/8	1-11/32	PLASTIC	X, F TO 1/30;ALL M SPEEDS
FLASH BAR	M	3,600	17	14	200,000	3-45	5500	LIN.ARRAY	4-1/4	1-13/16	CONTACT TAB	
SUPER-10	MF	1,800	13	10	140,000	1800 min.	5500	VERT.ARRAY	1-3/4	S-1/2	CONTACT TAB	X,F TO 1/40

NOTES: 3. MEASURED ALONG BEAM AXIS

(b) Typical multiple photoflash lamps

Figure 2.3-3

the other to the contact tab, permitting them to be fired sequentially be successive actuations of the shutter. After the four top flashbulbs have been fired, the Flip Flash is unplugged and reversed end for end, and the second edge connector is plugged in. This brings the four unfired flashbulbs to the top, to be fired sequentially as before. The flashbulbs being fired are at sufficient height above the camera lens to minimize the phenomenon in color photography called 'red eye' (caused by retroreflection of the flash from the retina). The internal switches eliminate lost exposures or wasted flashbulbs by selecting the next new top flashbulb to be fired even though the Flip Flash may have been removed and replaced after the previous flashbulb was fired.

Super 10 Flip Flash (Figure 2.3-5c) are similar to Flip Flash units, but have planar arrays of 10 bulbs. When the five top bulbs have been fired, the unit is reversed so that the remaining five bulbs can be fired.

Illuminating Characteristics

Since photoflash lamps emit light in flashes of brief duration, their characteristics may differ in form, units, or quantities from those of lamps having continuous outputs.

Time-Light characteristics of flash lamps are plots of their luminous outputs versus time. The time-light characteristics of single photoflash lamps are plots of luminous flux (lumens) versus time as shown in Figure 2.3-6, while the time-light characteristics of multiple photoflash lamps usually are plots of axial luminous intensity (frequently called beam candlepower) versus time as shown in Figure 2.3-7.

The reason for the use of different luminous units in Figures 2.3-6 and 2.3-7 is that multiple photoflash lamp arrays have built-in reflectors that concentrate the lamp outputs in beams, while single photoflash lamps are bare lamps which emit light over nearly a total sphere. Thus, the luminous flux outputs of single photoflash lamps can be measured, but their beam intensities when they are used in reflectors cannot be determined until the reflector characteristics are known.

Regardless of the type of ignition, the primer is generally ignited within about 5msec. The shape of the output curve is controlled to suit the specific applications of the flash lamp. For most lamps, the curve is designed to rise to peak output at from 5 to 30msec. Decay to near zero generally is within 50msec. as the foil is consumed. Lamps for use with focal plane shutters have a broad plateau rather than a narrow peak. One lamp (type FF33) for high speed photography and other special applications has a duration on the order of two seconds.

Flash lamp temporal performance is most simply characterized by two parameters. The first is the time from ignition to the peak of the output curve, called 'peak delay' or 'time to peak'. The second is the time between the two points on the output curve that are at one half of the maximum amplitude, called 'half-peak duration'. Photoflash lamps are grouped according to these properties in order to identify their synchronization characteristics. The peak delay for the various shutter synchronization classes are approximately as follows: Fast (F), 5-7msec; Medium-Fast (MF), 10-15msec; Medium (M), 17-22msec; Slow (S), 30msec. Focal Plane (FP) reaches near maximum in 12-15msec and maintains this value for tens of milliseconds.

Approximate peak outputs of the various types range from 0.3 to 6 million lumens for single photoflash lamps and from 0.1 to 0.3 million beam-candlepower for multiple photoflash lamps, and the peak outputs of clear lamps are about twice the peak outputs of blue lamps of the same type.

Total light output of each type of photoflash lamp is equal to the area under its time-light characteristic. The units of the quantities represented by these areas are lumen-seconds (over 4π steradians) for single photoflash lamps, and beam-candlepower-seconds (on axis) for multiple photoflash lamps. Typical values are shown in Figure 2.3-3. For types available in both clear and blue bulbs, the total light output of the clear lamps ranges from about 1 1/2 to 2 times greater than that of the blue lamps.

Polar intensity distribution. Single photoflash lamps emit light somewhat equally in all directions except that of the small solid angle obscured by their bases. This pattern is modified, and the forward intensity is greatly increased, by the reflector of the photoflash unit in which the lamp is used. The shape and size of the reflector and its surface finish (e.g. specular, diffuse, faceted, or peened) control not only the shape of the beam but the 'hardness' or 'softness' of the light. Some aspects of reflector designs are discussed in Section 9.

Since multiple photoflash lamps have built-in reflectors, their intensity distribution is predetermined. In general the beam angle is equal to or larger than the included angle of the lens on the camera with which the multiple photoflash lamp array is used.

Spectral energy distributions of typical clear and blue photoflash lamps are shown in Figures 2.3-8 and 2.3-9 respectively.

Color temperatures. Photoflash lamps with clear lacquer coatings generally have nominal correlated color temperatures of approximately 3800K, and those with blue lacquer coatings or blue plastic cases have nominal correlated color temperatures of approximately 5500K. The blue

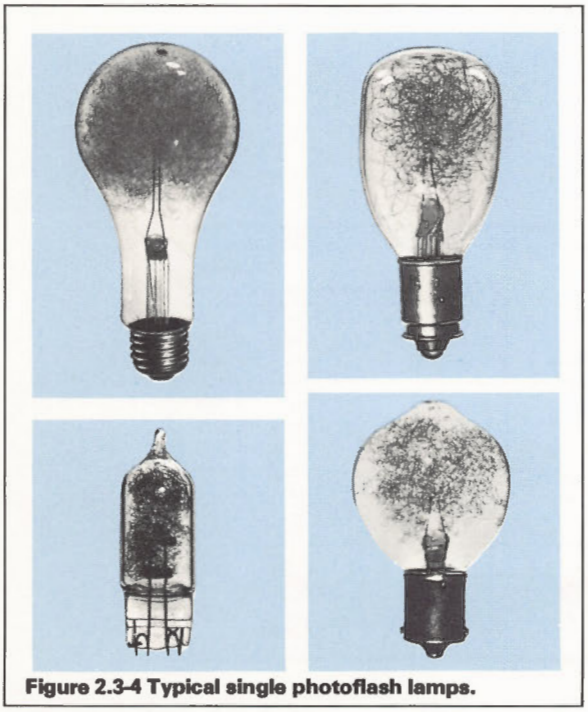
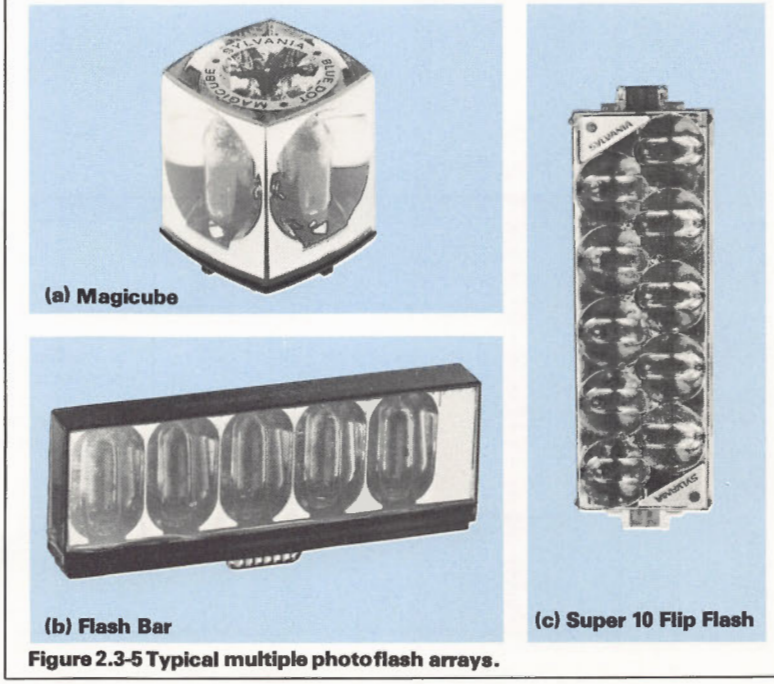


Figure 2.3-4 Typical single photoflash lamps.



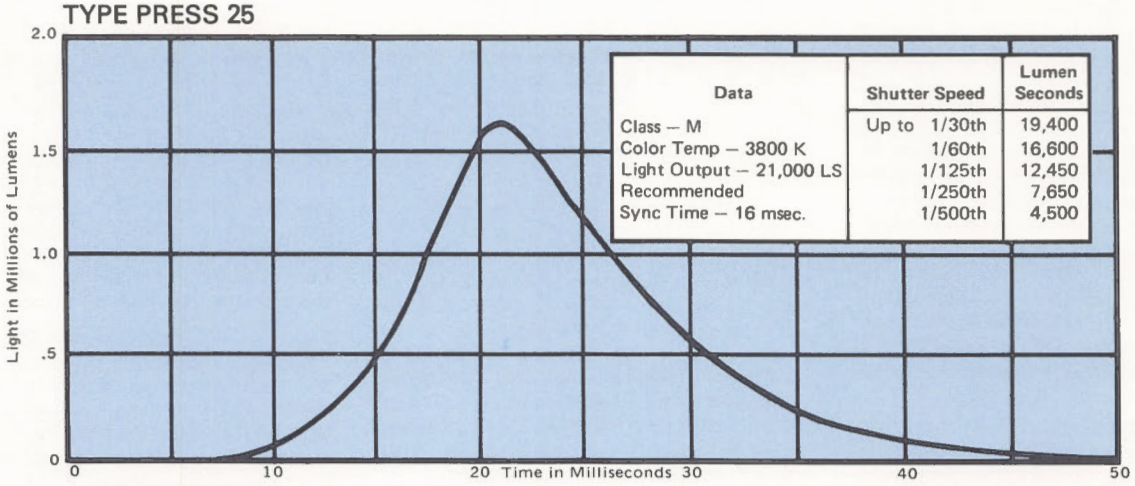
(a) Magicube

(b) Flash Bar

(c) Super 10 Flip Flash

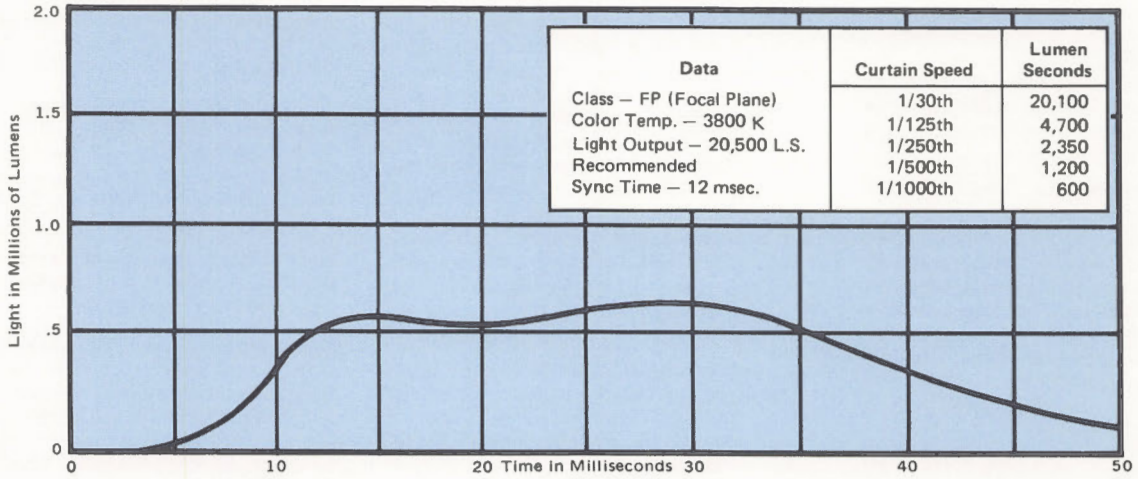
Figure 2.3-5 Typical multiple photoflash arrays.

TYPE PRESS 25



Data	Shutter Speed	Lumen Seconds
Class – M	Up to 1/30th	19,400
Color Temp – 3800 K	1/60th	16,600
Light Output – 21,000 LS	1/125th	12,450
Recommended	1/250th	7,650
Sync Time – 16 msec.	1/500th	4,500

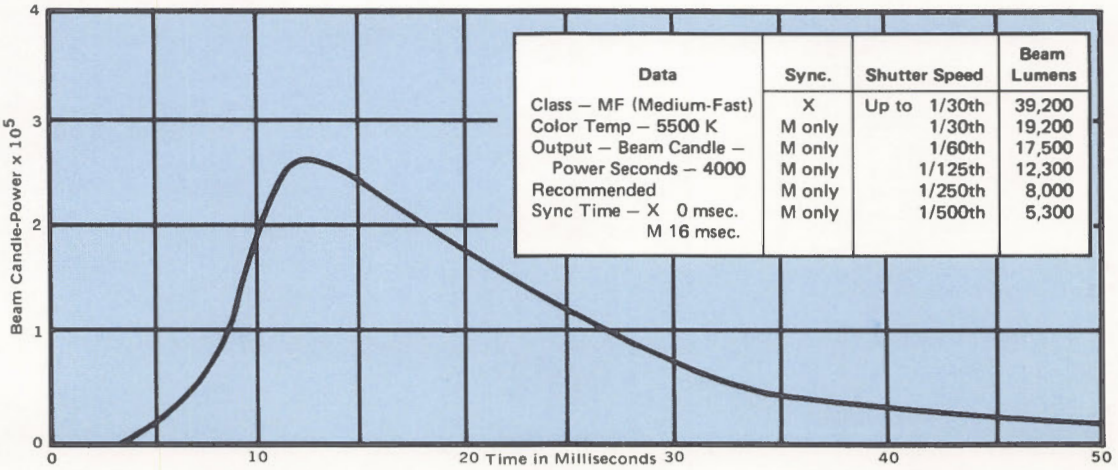
TYPE FP 26



Data	Curtain Speed	Lumen Seconds
Class – FP (Focal Plane)	1/30th	20,100
Color Temp. – 3800 K	1/125th	4,700
Light Output – 20,500 L.S.	1/250th	2,350
Recommended	1/500th	1,200
Sync Time – 12 msec.	1/1000th	600

Figure 2.3-6 Time-light characteristics of typical single photoflash lamps.

HI – POWER CUBE



Data	Sync.	Shutter Speed	Beam Lumens
Class – MF (Medium-Fast)	X	Up to 1/30th	39,200
Color Temp – 5500 K	M only	1/30th	19,200
Output – Beam Candle –	M only	1/60th	17,500
Power Seconds – 4000	M only	1/125th	12,300
Recommended	M only	1/250th	8,000
Sync Time – X 0 msec.	M only	1/500th	5,300
M 16 msec.			

Figure 2.3-7 Time-light characteristics of typical multiple photoflash lamp array.

lamps are called 'daylight lamps'. Both clear and blue lamps can be used with black-and-white films, but only blue lamps should be used with daylight type color films. In the latter case, the use of weak color-correcting lens filters is sometimes recommended by the film manufacturer as a means of improving color balance.

Operating Characteristics

Ignition Requirements

All single photoflash lamps, whether rated for operation at 3-45V or at 3-125V, can generally be ignited by a battery flash circuit of the type shown in Figure 2.3-10 or a battery-capacitor flash circuit of the type shown in Figure 2.3-11.

The battery flash circuit of Figure 2.3-10 employs two or three 1.5Vdc flashlight cells in series, and thus operates at about 3 or 4.5Vdc. The internal resistance of these dry cells is low enough so that they can supply the current (about 3A for about 1 to 3msec) required to fire the lamp when the circuit is closed by switch contacts synchronized to the camera shutter. The 'sync' switch contacts may be part of the shutter mechanism, or they may be inside a separate synchronizer. The times at which the switch closes and at which the camera shutter opens and closes are discussed below under Synchronizing Requirements.

The 3 to 4.5Vdc battery flash circuit is quite reliable when all contacts (e.g., between flashbulb and socket, and between sync cord plugs and jacks) are clean; but if contact resistances build up between uses, the current through the flashbulb filament may decrease to values at which ignition is less certain. This problem is mainly overcome by the battery-capacitor flash circuit of Figure 2.3-11 which employs batteries of higher voltage (e.g., 22.5V). These higher battery voltages cause more reliable ignition of photoflash lamps by reducing the effects of socket and sync contact resistances. However, the small transistor batteries used have relatively high internal resistances and thus cannot directly supply the current required to ignite photoflash lamps. This problem is overcome by the use of a storage capacitor which is charged by the battery between flashes and which discharges its stored energy through the photoflash lamp filament during flashes. The capacitance must be large enough so that the stored energy is at least the 10mJ required to ignite the lamps.

Note that the battery-capacitor flash circuit cannot operate unless a photoflash lamp is inserted into the socket to provide the needed continuity. Storage capacitor C (typically 100μF, 25Vdc) then charges to the terminal voltage of the battery (typically a 22.5Vdc transistor radio battery) through current-limiting resistor R (typically 1000 ohms, 1/2 watt) and the lamp filament. When the sync contacts are closed, capacitor C discharges its stored energy through the filament of the photoflash lamp in a current pulse of sufficient amplitude to heat the filament and ignite the primer. Since the capacitor is charged through the filament of the unfired photoflash lamp in the socket, unfired lamps should not be kept in the socket for extended periods of time, because the electrolytic capacitor will draw a small continuous current that will drain the battery.

Single 3-125V photoflash lamps (e.g., 2/B, 3/B) can also be operated from nominal 120 Vac lines as shown in Figure 2.3-12. Up to thirty lamps can be fired in series (Figure 2.3-12a), and up to ten lamps can be fired in parallel (Figure 2.3-12b). Although these 3-125V lamps have internal fuses designed to open before the ac line fuses, the inrush current may be so high when two or more are operated in parallel from 120Vac that even the internal lamp fuses do not protect the line fuses from being blown when the lamps are fired. For parallel operation, therefore, a 120V incandescent lamp of the wattage recommended in Figure 2.3-12c should be connected in series with the parallelled photoflash lamp.

Multiple 3-45V photoflash lamps (e.g., Flashcube, Hi-Power Flashcube and Flash Bar) can be operated from a battery flash circuit like that of Figure 2.3-10 or from a battery-capacitor flash circuit like that of Figure 2.3-11. A separate flash attachment generally is not required because each photoflash lamp plugs into the top of the camera designed to employ it, and the flash circuit components are built into the camera. As previously stated, the Flash Bar is used on the Polaroid SX-70 and similar cameras, and is ignited by the battery that is built into the film cartridge.

Flip Flash and Super 10 Flip Flash lamps are ignited by a 2000-3000V pulse from a piezoelectric element inside the camera which is struck by a hammer when the shutter is released.

Synchronization Characteristics

Synchronization of the flashlamp output with the camera shutter is exceedingly important in photoflash photography since only the light generated while the shutter is open will contribute to photographic exposure. Time allowance must be made for the delay between ignition and peak output of the lamp as well as for the shutter characteristics.

A temporal description of the flashlamp is provided by the curve of lumen or beam candlepower versus time. Several significant characteristics of these curves are illustrated in Figure 2.3-13; peak intensity, half peak intensity, total duration, half peak duration, peak delay, and half peak delay. Note that the one-third rather than the one-half peak duration is commonly used for electronic strobe lamps.

The rated luminous output of a flashlamp generally is based on total (time) output, i.e., it is the total integrated area under the intensity-time curve. This value is applicable when a shutter is open for the total duration of flashlamp output. Other ratings are used for the same flashlamp when only part of the output is utilized photographically due to (1) synchronization causing the shutter to open after light emission starts and/or (2) fast shutter settings causing the shutter to close before light emission has been completed. Figure 2.3-14 illustrates the various ratings for a type M3 flashlamp depending on synchronization and shutter setting. The lumen-second values are determined by the area under the curve during the time interval that the shutter is open. A further discussion of synchronization is found in Section 10.1.

Exposure Guide Numbers

Manufacturers of photoflash lamps and manufacturers of photographic films publish exposure guide numbers for each type of lamp and each type of film to aid in making correct

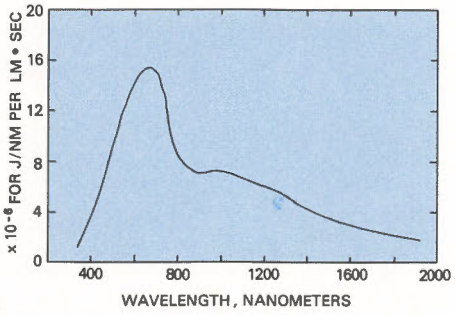


Figure 2.3-8 Approximate normalized spectral energy distribution of clear photoflash lamp 3800K correlated color temperature.

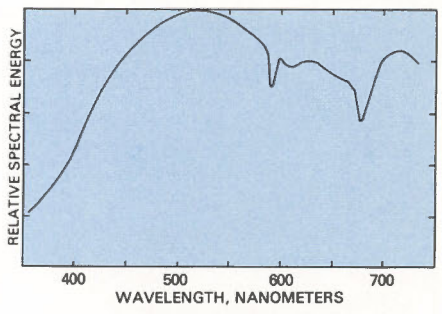


Figure 2.3-9 Relative spectral energy of flashbar at nominal color temperature of 5500K.

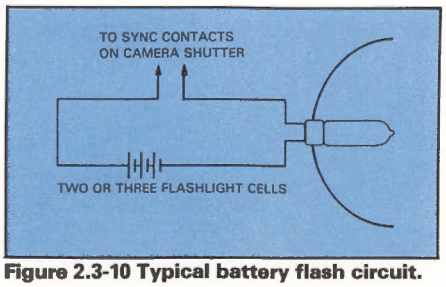


Figure 2.3-10 Typical battery flash circuit.

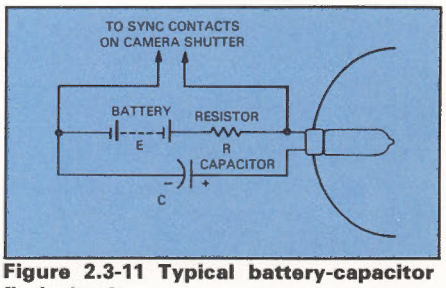


Figure 2.3-11 Typical battery-capacitor flash circuit.

exposures. Guide numbers are expressed as follows: (guide number) = (lens f-number) x (lamp-to-subject distance, feet). American National Standard PH 2.4-1965, "Exposure Guide Numbers for Photographic Lamps" gives the following formula for guide numbers for bare photoflash lamps:

$$\mathbf{GN} = \sqrt{0.004\ (\mathbf{Lt})\ \mathbf{MS}}$$, where (eq. 2.3-1)

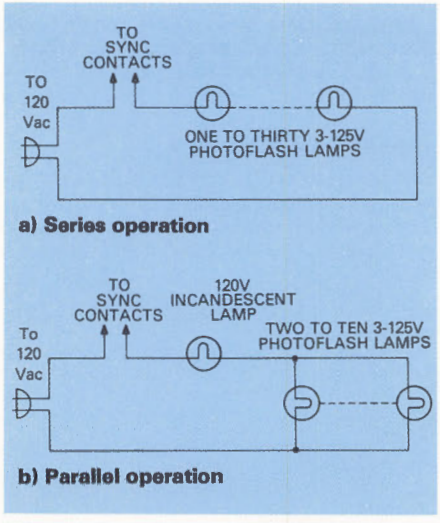
GN = guide number
Lt = lumen-second rating of photoflash lamp (integrated while shutter is open)
M = reflector factor
S = ASA film speed (arithmetic)

For multiple photoflash lamps which have built-in reflectors of known characteristics, and the outputs of which are rated in beam candlepower, the guide number is given by:

$$\mathbf{GN} = \sqrt{0.05\ (\mathbf{ECPt})\mathbf{S}}$$, where (eq. 2.3-2)

(ECPt) = effective beam candlepower-seconds (integrated while shutter is open)

The reflector factor (**M**) is the ratio of the axial candlepower-seconds of the reflector-lamp combination to the mean spherical candlepower of the bare lamp. Typical values given in PH2.4-1965 are shown in Figure 2.3-15.



Photoflash Lamps in Parallel	Wattage of Series 120V Incandescent Lamp
2	150 - 200
3	200 - 300
4 - 5	300 - 500
6 - 10	1000

c) Recommended wattages of series incandescent lamp for parallel operation of two to ten 3-125V photoflash lamps)

Figure 2.3-12 Operation of 3-125V photoflash lamps from 120Vac lines.

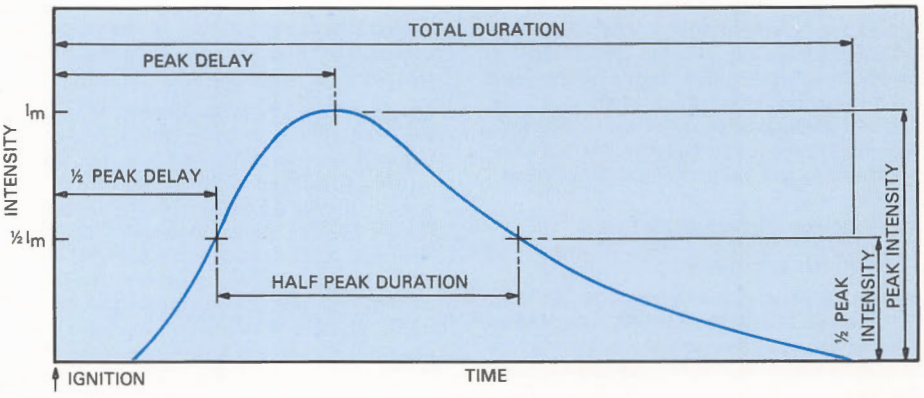


Figure 2.3-13 Time-light characteristics for photoflash lamps.

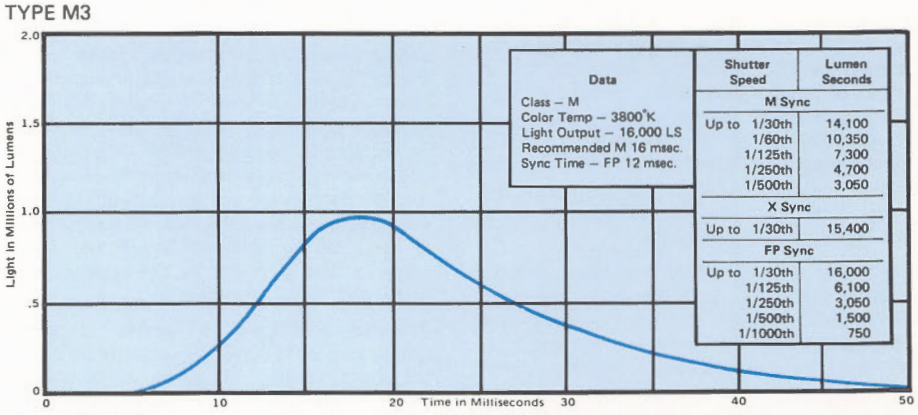


Figure 2.3-14 Lumen-second ratings of the M3 flashlamp for various operating conditions.

LAMPS	SMALL POLISHED REFLECTORS	SMALL MEDIUM DIFFUSE REFLECTORS	POLISHED REFLECTORS	MEDIUM DIFFUSE REFLECTORS	LARGE STUDIO REFLECTORS
	DIAMETER 3 TO 4 TIMES LAMP DIA		6-1/2 IN. TO 7-1/2 IN. DIA	6-1/2 IN. to 7-1/2 IN. DIA	ABOVE 12 IN. DIA
SMALL LAMPS (UP TO 1-1/2 IN. DIA)	8-12	6	–	–	–
MEDIUM LAMPS (1-5/8 IN. TO 2-1/2 IN. DIA)	–	–	6	4	–
LARGE LAMPS (ABOVE 2-1/2 IN. DIA)	–	–	–	4	6

Figure 2.3-15 Reflector factor M for various reflector-lamp combinations.

3.0 Low-Pressure Discharge Lamps

These gaseous discharge lamps operate at pressures ranging from the order of 10^{-6} to the order of 10^{-3} atmosphere. There are two major types of low-pressure discharge lamps; low-pressure mercury lamps and low-pressure sodium lamps.

Low-pressure mercury lamps include a large variety of fluorescent lamps (with broadband spectral outputs for general illumination, or with various narrowband spectral outputs for specific applications) and non-fluorescent lamps (e.g., germicidal lamps and ozone-producing lamps). Since even the non-fluorescent types are generally made by techniques similar to those used in the fabrication of the fluorescent types, the entire group of low-pressure mercury lamps is usually categorized under the heading of fluorescent lamps.

Low-pressure sodium lamps are a small group of high-efficacy lamps which are generally employed for illumination in applications where their nearly-monochromatic yellow output is acceptable.

3.1 Fluorescent Lamps

The fluorescent lamp generates ultraviolet radiation by means of a mercury arc discharge in an inert gas (e.g., argon, krypton, neon) at low pressure. The ultraviolet radiation (mainly at the 253.7nm mercury line) causes a phosphor coating on the inner surface of the lamp bulb to fluoresce, and thus to produce light. The phosphor acts as an energy converter that transforms the invisible ultraviolet radiation into longer-wavelength visible radiation.

There are two categories of fluorescent lamps: (1) cold-cathode lamps, which operate in the glow-discharge mode, with currents in the order of a few hundred milliamperes, and with a cathode potential drop exceeding 50V; and (2) hot-cathode lamps, which operate in the arc-discharge mode, with currents up to 4A, and with a cathode-potential drop in the order of 10 to 12V. This low cathode-potential drop permits high efficiency so that most fluorescent lamps are of the hot-cathode type. All of the lamps described in this section are hot-cathode fluorescent lamps.

Principles of Operation

The operating principles of hot-cathode fluorescent lamps are illustrated in Figure 3.1-1. The lamp is usually a tube, the inner surface of which is coated with a phosphor. The tube is filled with mercury vapor in an inert gas at a pressure of about 0.0013 to 0.0053 atmosphere, and is sealed at the ends. Electrodes inside the ends of the tube have leads which pass through the seals.

The hot cathodes are filamentary electrodes that are heated to temperatures at which thermionic emission occurs, i.e., they emit electrons. A voltage applied between the electrodes establishes an electric field in the tube. The negative electrode is called the cathode and the positive electrode is called the anode. (If the applied voltage is ac, each electrode is a cathode when negative and an anode when positive.) The thermal electrons emitted by the cathode are accelerated along the tube until they collide with one of the two outer-orbit valence electrons of a mercury atom. The valence electron absorbs kinetic energy from the accelerated electron and is raised to one of several possible higher energy levels (i.e., is 'excited') or is completely knocked out of its orbit (leaving behind a positively charged 'ionized' mercury atom) to become itself a free electron, which is then accelerated along the tube to excite and ionize other mercury atoms. This process is cumulative and continues to the point where it is self-sustaining (i.e., the rate of production of new electron-ion pairs matches the rate of loss) forming an arc discharge. The function of the

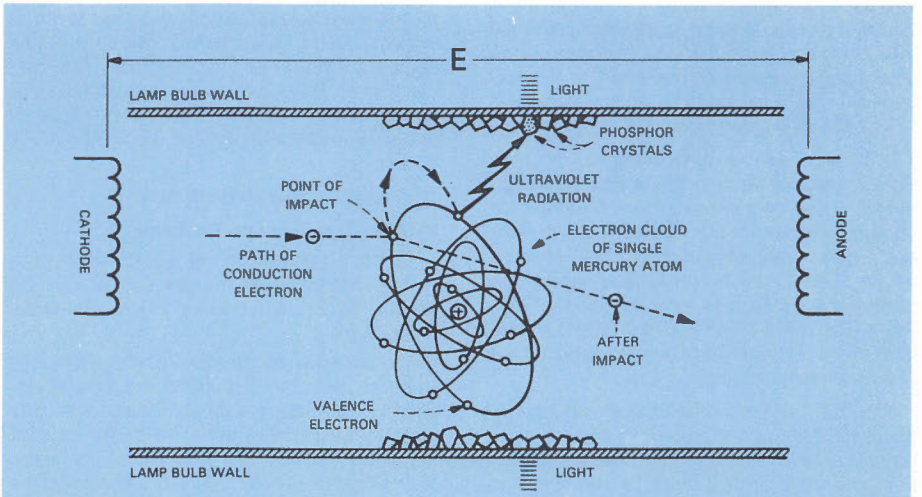


Figure 3.1-1 Operating principles of hot-cathode fluorescent lamps.

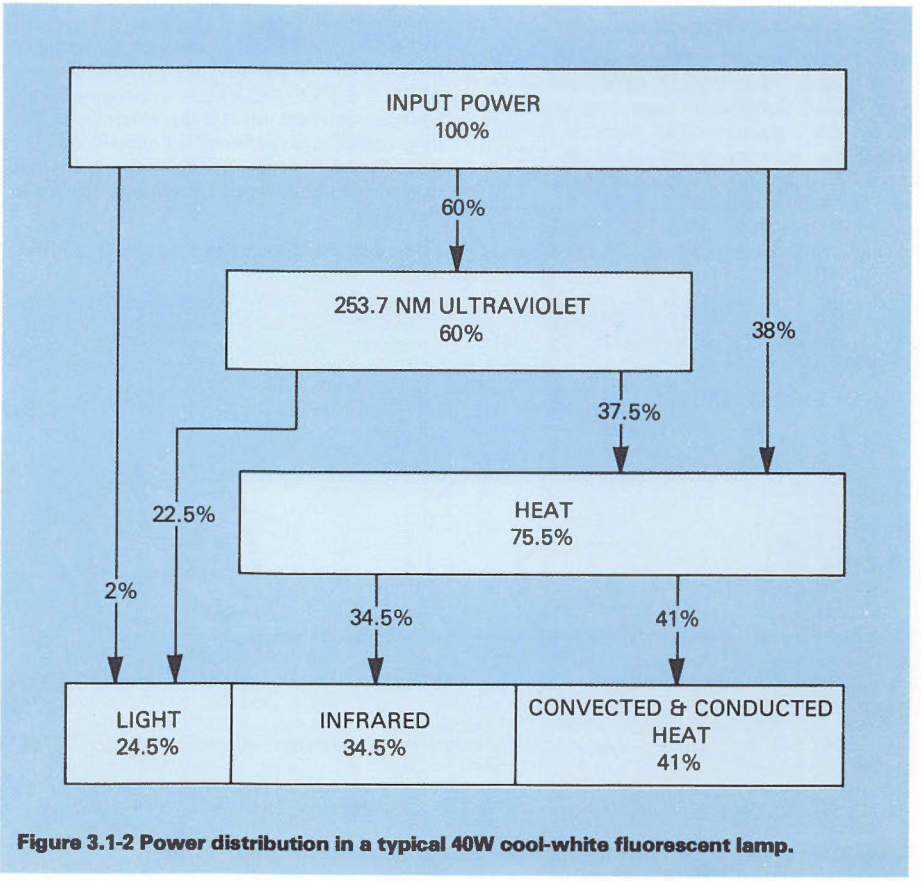


Figure 3.1-2 Power distribution in a typical 40W cool-white fluorescent lamp.

inert gas is to prevent the electrons from following a direct path between the cathode and the anode. As a result of collisions with the inert gas atoms, the electrons are forced into a zig-zag course which greatly increases the chances of collision with mercury atoms.

Although each free electron loses speed and kinetic energy and changes direction as a result of collision with a mercury valence electron, or as a result of 'elastic' collisions with rare gas atoms, it continues to be accelerated along the tube by the electric field, to excite or ionize other mercury atoms before it falls to the wall (where it recombines with an ionized atom) or is collected at the anode.

Each excited mercury valence electron almost instantly returns to its normal energy level in one or more steps, at each of which a photon, or quantum of radiant energy, is emitted. This emission of photons, called radiation, occurs at the characteristic wavelengths of the various spectral lines of mercury: 185.0, 253.7, 365.4, 404.7, 435.8, 546.1, 578.0nm, etc. About 60% of the electrical input power appears at the 253.7nm ultraviolet line.

The 253.7nm ultraviolet photons emitted by the excited mercury atoms strike the phosphor crystals on the inner surface of the tube. Each photon passes through a crystal until it hits an activator ion. If the photon wavelength is within the phosphor excitation band, the photon will be absorbed and a photon of longer wavelength (e.g., near-ultraviolet or visible) will be released. The phosphors are designed to be activated mainly by the 253.7nm line, and to produce light of desired spectral distributions.

Figure 3.1-2 shows the per cent of electrical input power to a typical 40W cool-white (F40T12CW) fluorescent lamp that is transformed into light and other forms of power. Taking the electrical input power as 100%, about 2% is converted into visible radiation at various mercury lines, 60% is converted into ultraviolet radiation at the 253.7nm mercury line, and 38% becomes heat. Of the 60% at 253.7nm, 22.5% is converted into visible radiation by the phosphor, and 37.5% becomes heat. The total amount of heat generated is thus 75.5%, some of which (34.5%) appears as infrared radiation and some (41%) as sensible heat which must be removed by conduction and convection. Of the original 100%, 24.5% is converted into light, producing about 3150 initial lumens and 2770 mean lumens over a rated life of 20,000 hours. The initial efficacy is thus about 80 lm/W excluding ballast losses, and about 68 lm/W including ballast losses. This data may be compared to that of a typical 120V, 150W incandescent lamp, which has about the same lumen output (2850 lm), and an efficacy of about 19 lm/W with a rated life of about 750 hours.

Physical Characteristics

Typical Construction Features

Figure 3.1-3 shows the construction of a typical hot-cathode fluorescent lamp. The various parts are explained in the following paragraphs.

Bulbs are generally tubular, with large ratios of length to diameter. Both dimensions usually increase with wattage ratings, from about 4 watts for the six-inch T5 lamp to about 215 watts for the ninety-six-inch T12 VHO lamp. The diameters range from 5/8″ to 2-1/8″. The bulbs are designated by a letter for the shape (T for tubular) and a number expressing the diameter in eighths of an inch. The 5/8″ diameter bulb is thus designated T5 and the 2-1/8″ diameter bulb is designated T17. Most bulbs are straight in nominal overall lengths (including allowances for the axial thicknesses of standard lampholders) from 6″ to 96″. In Circline lamps the tubes are bent into circles having nominal diameters of 6½″, 8″, 12″ and 16″; in Curvalume lamps the tubes are bent into a U that is nominally 24″ long and 6″ wide between leg centerlines. The glass used is generally transparent, except that in blacklight-blue lamps the glass is opaque in the visible.

Hot-cathode electrodes are coils of tungsten wire, coated with a mixture of alkaline earth oxides (e.g., barium, strontium and calcium oxides), that emit electrons when heated to temperatures above 950°C (1223K). The thermionic emission of electrons from these hot cathodes is so copious that it reduces the starting voltage required to initiate the arc discharge. Cathode designs vary depending on lamp loading and on whether they are intended for use in preheat, rapid-start, or instant-start lamps.

The gas fill is mercury vapor at a pressure of about 0.006 torr (about 8×10^{-6} atm) in an inert gas (e.g., argon, krypton, neon) at a pressure of about 1 to 4 torr (about .0013 to .0053 atmosphere). The mercury vapor pressure corresponds to a condensation temperature of 40°C, which is the nominal operating temperature of most fluorescent lamps.

The phosphors used to coat the inner surfaces of the bulbs are extremely pure crystalline compounds with very small amounts of activators added to increase the efficiency of fluorescence and thus the light output. Combinations of different types and proportions of phosphors and activators are used to achieve a wide variety of spectral power distributions which include a large range of whites and near-whites for general illumination, plus colors such as red, pink, gold, green and blue, and near-ultraviolet.

Other coatings may be applied to the inner surfaces of the bulbs before the phosphor is deposited, to control the spectral or spatial distribution of the light output. Red and gold fluorescent lamps have translucent or transparent filter coatings applied to the entire inner surfaces of the bulb walls, while reflector and aperture lamps have semi-opaque reflector coatings applied in longitudinal strips subtending various central angles.

Bases for fluorescent lamps are shown in Figure 3.1-4. Most hot-cathode lamps require two contacts at each end; bipin bases are generally used, with recessed-double-contact bases being employed in high-output and very-high-output types. Circline lamps, in which the two ends are close together, have one four-pin base. Slimline instant-start lamps and Signline lamps require only one contact at each end, so that they have single-pin bases. Single-contact ferrule bases are used only on 'aircraft' type fluorescent lamps.

Lampholders (sockets) for fluorescent lamps are shown in Figure 3.1-5. Twist-turn lampholders are most commonly used for lamps with bipin bases; push-pull lampholders are sometimes used. Special circuit-interrupting bipin lampholders are used with some single-lamp ballasts and dimming ballasts. The two single-pin lampholders for Slimline lamps are not identical; the 'high-voltage' lampholder is moveable, while the 'low-voltage' lampholder has a circuit-interrupting feature which prevents voltage from being applied to the lamp until both pins are seated.

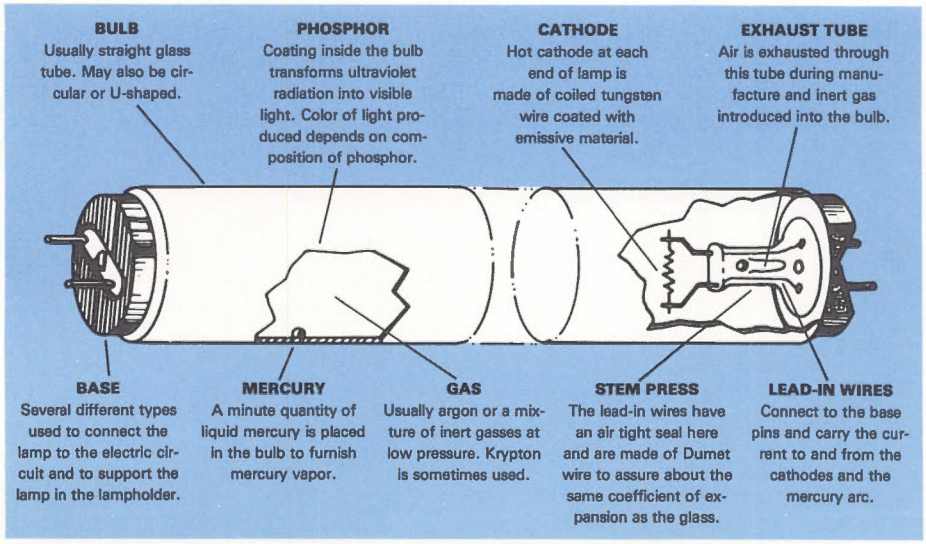

BULB
Usually straight glass tube. May also be circular or U-shaped.
PHOSPHOR
Coating inside the bulb transforms ultraviolet radiation into visible light. Color of light produced depends on composition of phosphor.
CATHODE
Hot cathode at each end of lamp is made of coiled tungsten wire coated with emissive material.
EXHAUST TUBE
Air is exhausted through this tube during manufacture and inert gas introduced into the bulb.
BASE
Several different types used to connect the lamp to the electric circuit and to support the lamp in the lampholder.
MERCURY
A minute quantity of liquid mercury is placed in the bulb to furnish mercury vapor.
GAS
Usually argon or a mixture of inert gasses at low pressure. Krypton is sometimes used.
STEM PRESS
The lead-in wires have an air tight seal here and are made of Dumet wire to assure about the same coefficient of expansion as the glass.
LEAD-IN WIRES
Connect to the base pins and carry the current to and from the cathodes and the mercury arc.

Figure 3.1-3 Construction of a typical hot-cathode fluorescent lamp.

Types of Fluorescent Lamps

Types Categorized By Starting Characteristics

Regardless of their shapes and functions, all hot-cathode fluorescent lamps can be catego-

rized in terms of their starting characteristics as preheat, instant-start, or rapid-start types. Each type requires auxiliary circuits employing ballasts (and sometimes starters) designed to match its starting characteristics.

Preheat fluorescent lamps (1938) require separate starters which supply current through the cathodes to preheat them for the few seconds from the time of turn-on to the time the lamp lights. Preheating causes the cathodes to emit thermionic electrons that permit striking the arc at a lower voltage. When the preheating current is cut off, a high-voltage spike is generated which ignites the lamp. During normal lamp operation, the cathodes are heated by the arc discharge. Preheat fluorescent lamps have bipin bases, ratings from 4W to 90W, and lengths from 6 to 60 inches. Ordering designations identify preheat fluorescent lamps by wattage, bulb diameter in eighths of an inch, and color. Thus the F20T12/CWX is a 20W, 1½″ diameter, cool-white-deluxe, preheat fluorescent lamp. Miniature preheat lamps in T5 bulbs are available in 4W to 13W ratings. Preheat lamps in T8 bulbs are used in desk lamps and in general lighting.

Instant-start fluorescent lamps (1944) operate without starters. Since the cathodes are not preheated, single-pin bases can be used as in Slimline, Signline, and Coachline lamps. These have ratings from 9W to 114W and lengths from 24 to 96 inches. Because they can be operated at more than one loading, they are designated by length instead of wattage. Thus the F96T12/CW is a 96″ long, 1½″ diameter, cool-white, Slimline fluorescent lamp. The normal wattage (75W) does not appear in the lamp-ordering abbreviation. There are several 40W instant-start lamps with bipin bases; since only one pin is required, the two pins at each end are connected together inside the base. The designations for these bipin instant-start lamps have the suffix IS. Thus the F40T12D/IS is a 40W, 1½″ diameter, daylight, instant-start fluorescent lamp. Note that bipin instant-start lamps will fit into the lampholders of preheat or rapid-start lamp luminaires, but they will not operate in those luminaires and might cause ballasts to overheat.

Rapid-start fluorescent lamps (1952) operate without starters. The cathodes are heated continuously from turn-on to turn-off by coil-heat windings in the ballast. Starting is almost as rapid as in instant-start lamps. Standard rapid-start lamps are available in straight T12 bulbs in 30W (36″) and 40W (48″) sizes. The 30W size has a complete designation, such as F30T12/CWX/RS, where the suffix RS means rapid-start; but the 40W size is so popular that the T12 bulb size and the RS suffix are omitted. For example, F40N is a 40W, 1½″ diameter, natural, rapid-start fluorescent lamp. All rapid-start lamps are silicone coated to provide reliable starting even under conditions of high humidity. The standard rapid-start lamps in T12 bulbs generally operate at 430 mA with a loading of 10W per foot. Rapid-start lamps are also available for heavier loadings, as High-Output (HO) and as Very-High-Output (VHO) lamps.

Types Categorized By Loading

Preheat, instant-start slimline, and standard rapid-start lamps with T12 bulbs generally operate at 10W/ft with 430 mA lamp current.

High-Output (HO) lamps generally operate at about 14W/ft with 800 mA lamp current in indoor applications.

Very-High-Output (VHO) lamps operate at about 25W/ft with 1500 mA lamp current.

Super-Saver lamps are available in the following categories: standard rapid-start, Slimline, High-Output, and Very-High-Output. Super-Saver lamps are characterized by lower wattage consumption and lower light output than their conventional counterparts.

Types Categorized By Function and Shape

Signline lamps are HO instant-start lamps that have shrouded single-pin bases for reliability in signs and other outdoor applications.

Low-Temperature lamps are VHO lamps designed for operation at low temperatures. Special low-temperature ballasts must be used to provide the higher starting voltages required.

Weather-Shielded lamps are fluorescent lamps encased in T14½ (1-13/16″ diameter) glass jackets for operation in extreme cold and high winds, conditions in which unjacketed lamps are inefficient or even inoperable. Several sizes of Slimline, High-Output, and Very-High-Output lamps are available in Weather-Shielded versions.

Circline lamps are tubular fluorescent lamps bent into nearly closed circles. A four-pin base at the gap connects to the cathodes at both ends.

Curvalume lamps are standard 40W lamps bent into a U-shape with a nominal length of 24″ and a 6″ distance between the centerlines of the legs.

Reflector fluorescent lamps are partially internally coated with a reflective coating before the phosphor coating is applied. The reflector provides directional control with approximately 60% more light in the forward direction than comparable non-reflector lamps. They are available from stock with 135° and 235° reflectors.

Aperture fluorescent lamps are similar to reflector lamps except for a small clear window in the reflector and phosphor coatings that runs the full length of the lamp. These lamps are available from stock with 30° and 60° apertures and provide significantly higher luminances than comparable standard lamps. Special aperture and reflector designs can be manufactured for OEM customers.

Super-Diazo-Blue (SDB) lamps have phosphors which produce radiation mainly in the 420nm region where many diazo materials are most sensitive. Because in most copying machine applications the fluorescent lamps are operated at high currents, these lamps have specially-designed heavy-duty cathodes.

Gro-Lux lamps produce radiant energy in the red and blue wavelengths that match the absorption spectrum of chlorophyll. The Standard Gro-Lux lamp is designed for home use, and the Gro-Lux Wide-Spectrum lamp is designed for commercial growers.

Blacklight lamps use a phosphor that radiates mostly in the near ultraviolet. It also emits some visible blue which may be suppressed by means of an external filter that transmits ultraviolet and blocks visible radiation.

Blacklight-blue lamps are similar to blacklight lamps except that the bulbs are made of a dark-

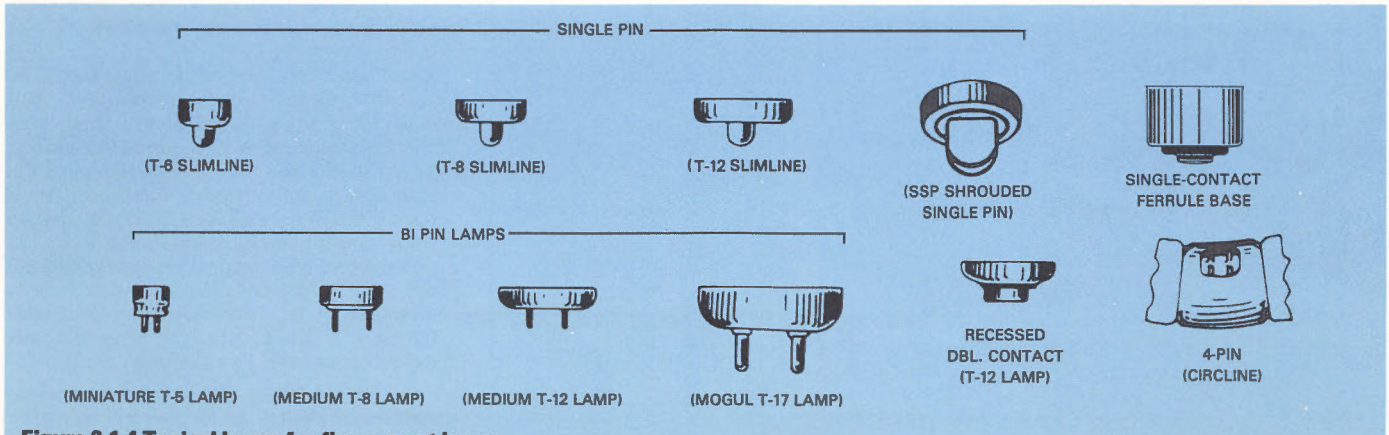


Figure 3.1-4 Typical bases for fluorescent lamps.

blue glass that absorbs in the visible and transmits in the ultraviolet. This eliminates the need for an external filter.

Germicidal lamps are similar to fluorescent lamps but have no phosphors so that they radiate the spectral lines of mercury. Most glasses absorb below about 280-300nm, but germicidal lamps are made of a special glass that transmits the strong germicidal 253.7nm ultraviolet line and does not transmit the 185nm ozone-generating line.

Ozone-producing lamps are similar to germicidal lamps but are made of a glass that transmits the 185nm ultraviolet line of energy. Absorption of this ultraviolet radiation by oxygen molecules in the atmosphere results in the production of ozone, a powerful germicide and oxidant. Such lamps should be used only in equipment designed to prevent the release of ozone at levels above the toxic limit into inhabited spaces.

Illuminating Characteristics

Lumen Output, Luminance, and Efficacy

Lumen outputs of fluorescent lamps are functions of loading (watts per unit length), nominal length, bulb diameter, color, ambient temperature, and burning time. Initial lumens are measured at 100 hours of operation because lumen output decreases somewhat during the first 100 hours, after which it decreases more slowly to the end of lamp life. Mean lumens throughout rated average life are approximately equal to the lumens measured at 40% of rated average life. Comparison of the initial/mean lumen outputs of nominal 48″ long, cool-white rapid-start lamps operating at different loadings shows that the F40T12 rapid-start lamp (430 mA and 10W/ft) produces 3150/2770 lumens, the F48T12/HO High-Output lamp (800 mA and 14W/ft) produces 4300/3740 lumens, and the F48T12/VHO Very-High-Output lamp (1500 mA and 25W/ft) produces 6750/5200 lumens.

Luminance of typical fully-coated fluorescent lamps is given approximately by:

$$\mathbf{L} = \frac{\text{lamp lumens}}{9.25\ \mathbf{d}\ \mathbf{e}}\text{, where} \qquad \text{(eq. 3.1-1)}$$

L = average luminance, cd/cm²
d = lamp diameter, cm
e = luminous length, cm

The average luminance of a fully-coated 40W cool-white fluorescent lamp is about 0.8 cd/cm². Luminance can be increased in any preferred direction by the use of internal reflectors, as in reflector and aperture fluorescent lamps, at the expense of decreased total output as well as decreased luminance in other directions.

Efficacies of fluorescent lamps of a given type and color increase with bulb length because the cathode power loss remains constant while the total input power and the percentage of input power converted to light both increase with length. Comparison of the initial/mean efficacies of nominal 48″ cool-white rapid-start lamps operating at different loadings shows that the F40T12 rapid-start/preheat lamp has 80/70 lm/W, the F48T12/HO has 72/62 lm/W, and the F48T12/VHO has 59/45 lm/W. Thus, while lumen output increases with loading, efficacy decreases. Even when ballast losses are included, the net efficacies are still significantly higher than those of incandescent lamps (59 lm/W mean efficacy for the F40CW vs. 19 lm/W for a 150W incandescent lamp).

Spectral Power Distribution and Color Temperature

The optical radiation from fluorescent lamps consists of the mercury lines at 365.4, 404.7, 435.8, 546.1, 578.0nm, etc., and the continuous fluorescent spectrum emitted by the phosphor. The 253.7nm mercury line that causes most of the fluorescent effect in the phosphor does not appear in the output because the energy at that wavelength is absorbed by the phosphor or by the lime glass of which most bulbs are made.

Figure 3.1-6 shows the spectral power distributions of typical Sylvania 40W fluorescent lamps for general illumination. For convenience, the power in each mercury line is shown as a 10nm-wide vertical bar centered about the actual wavelength of the line. Note that the area under each curve represents the total spectral-power output of the lamp for that wavelength band, and that the spectral power in the mercury lines, which is represented by the area under the bars, is much less than the spectral power in the continuous radiation. Figure 3.1-7 lists similar data in tabular form, showing the power outputs in arbitrary color bands.

Neither Figure 3.1-6 nor Figure 3.1-7 indicates how colored surfaces will appear when illuminated. Although a light source may appear white and may make white surfaces appear white, it may have poor color rendition. The standard white colors (cool-white, warm-white, white, and daylight) give high efficacies and good color rendition for most applications (e.g., work and office areas, and schools). The cool-white-deluxe, warm-white-deluxe, and natural lamps all trade efficacy for improved color rendition. This occurs because the human eye has low sensitivity to the red which makes up a large proportion of the output of deluxe lamps, so that those lamps have about 30% less lumen output than the standard white lamps. However, the increased vividness of color rendition tends to minimize the perceived reduction in light output. Incandescent fluorescent lamps trade off even more efficacy in order to achieve color rendition approximately equal to that of conventional incandescent lamps. Figure 3.1-8 compares the efficacies and color characteristics of typical white and colored 40W fluorescent lamps, and lists apparent color temperatures for the white lamps.

The spectral power distributions of lamps for various specialized applications are shown in Figure 3.1-9 (narrow-band colored lamps), Fig-

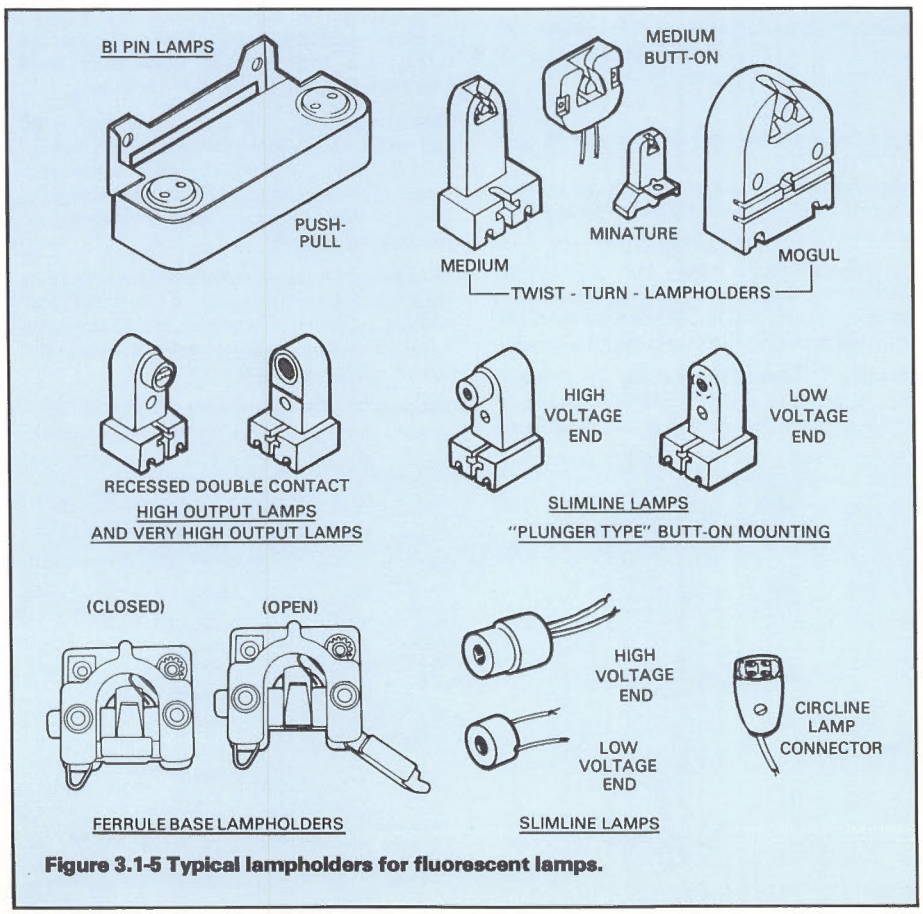


Figure 3.1-5 Typical lampholders for fluorescent lamps.

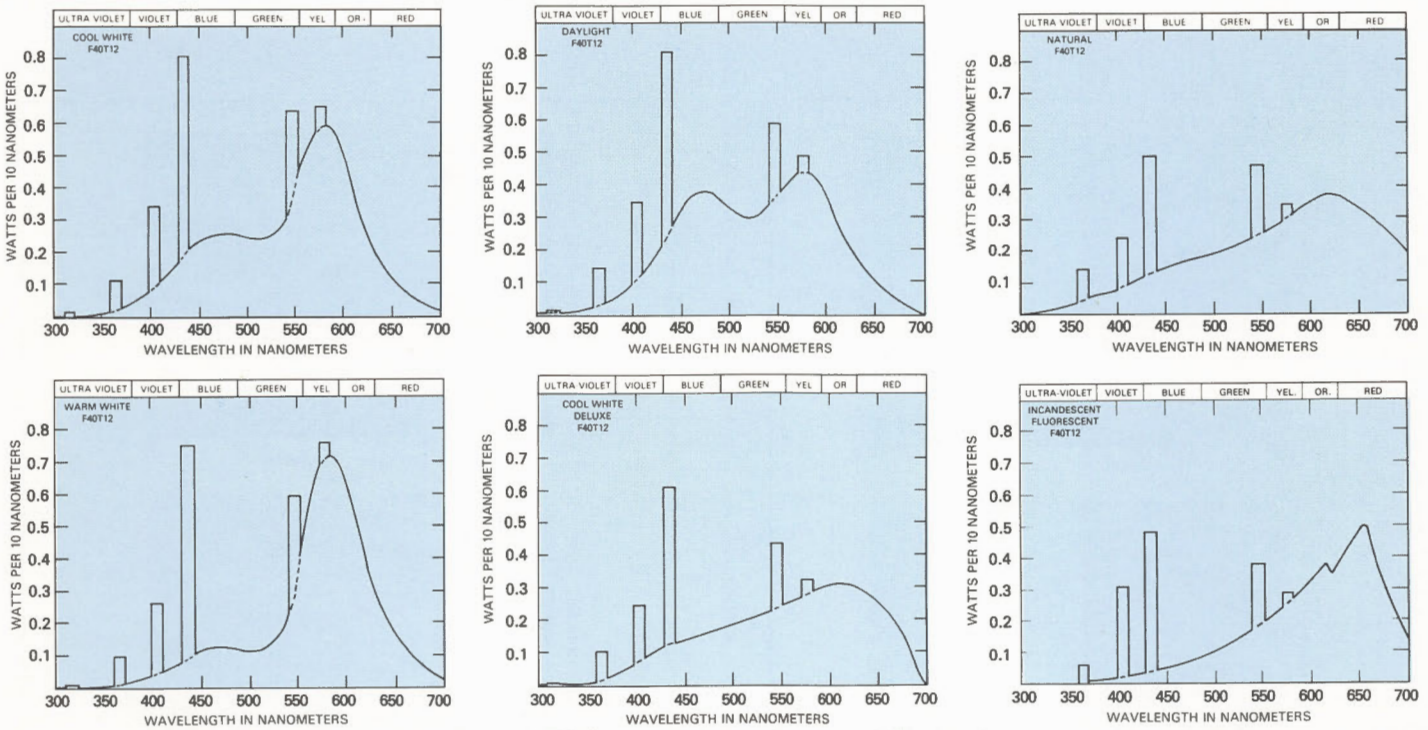


Figure 3.1-6 Spectral power distributions of typical F40 fluorescent lamps for general illumination.

SPECTRAL BAND	ULTRAVIOLET <380		VIOLET 380 - 430		BLUE 430 - 490		GREEN 490 - 560		YELLOW 560 - 590		ORANGE 590 - 630		RED 630 - 800		TOTAL	
WAVELENGTH, NM	W	%	W	%	W	%	W	%	W	%	W	%	W	%	W	%
COOL WHITE	.34	3.5	.65	6.7	1.85	19.2	2.29	23.8	1.86	19.3	1.70	17.7	.94	9.8	9.63	100.0
WARM WHITE	.21	2.3	.42	4.8	1.09	12.4	1.67	18.9	2.11	23.9	2.20	24.9	1.13	12.8	8.83	100.0
DAYLIGHT	.28	3.0	.86	9.0	2.55	26.8	2.47	25.9	1.46	15.3	1.18	12.4	.72	7.6	9.52	100.0
COOL WHITE DELUXE	.56	6.2	.56	6.2	1.26	13.9	1.87	20.6	.96	10.5	1.34	14.8	2.52	27.8	9.07	100.0
INCANDESCENT FLUORESCENT	.07	1.0	.15	2.2	.46	6.7	1.17	17.1	.75	11.0	1.28	18.7	2.96	43.3	6.84	100.0
BLUE	.32	3.9	1.43	17.5	3.66	44.9	2.08	25.5	.11	1.3	.34	4.2	.22	2.7	8.16	100.0
COOL GREEN	.20	2.4	.67	7.9	1.97	23.2	2.79	32.9	1.14	13.4	.96	11.3	.75	8.9	8.48	100.0
GREEN	.21	2.4	.21	2.4	.53	6.0	6.50	74.1	.97	11.1	.26	3.0	.09	1.0	8.77	100.0
GOLD					.01	0.2	.74	14.6	1.28	25.3	1.74	34.3	1.30	25.6	5.07	100.0
PINK	.08	1.4	.13	2.3	.37	6.7	.26	4.7	.54	9.8	1.84	33.3	2.31	41.8	5.53	100.0
RED											.12	8.2	1.35	91.8	1.47	100.0
GRO-LUX	.12	1.9	.49	7.5	1.53	23.5	1.01	15.5	.17	2.6	.42	6.5	2.77	42.5	6.51	100.0
GRO-LUX WIDE SPECTRUM	.23	3.0	.73	9.5	1.16	15.1	1.11	14.4	.77	10.0	1.24	16.1	2.46	31.9	7.70	100.0
BLACKLIGHT	10.53	83.8	.96	7.6	.63	5.0	.30	2.4	.09	0.7	.01	0.1	.04	0.4	12.56	100.0
BLACKLIGHT BLUE	9.25	91.9	.73	7.2	.05	0.5	.02	0.2	.01	0.1			.01	0.1	10.07	100.0

Figure 3.1-7 Spectral power distribution in arbitrary color bands of F40 fluorescent lamps.

LAMP COLOR DESIGNATION	ABBREV.	LAMP EFFICACY LM/W	CIE CHROMATIVITY X	CIE CHROMATIVITY Y	CORRELATED COLOR TEMP.	CIE COLOR-RENDERING INDEX
COOL-WHITE	CW	80	0.37	0.38	4300K	67
WARM-WHITE	WW	80	0.43	0.40	3100K	55
DAYLIGHT	D	66	0.31	0.33	6500K	77
WHITE	W	80	0.41	0.39	3600K	59
COOL-WHITE-DELUXE	CWX	55	0.37	0.36	4100K	86
WARM-WHITE-DELUXE	WWX	55	0.43	0.40	3000K	75
NATURAL	N	53	0.39	0.36	3800K	86
INCANDESCENT FLUORESCENT	IF	43	0.45	0.41	2700K	90
RED	R	5	0.70	0.30		
PINK	PK	32	0.54	0.34		
GOLD	GO	50	0.53	0.47		
GREEN	G	108	0.25	0.63		
BLUE	B	34	0.18	0.19		

Figure 3.1-8 Efficacies and color characteristics of typical white and colored 40W fluorescent lamps.

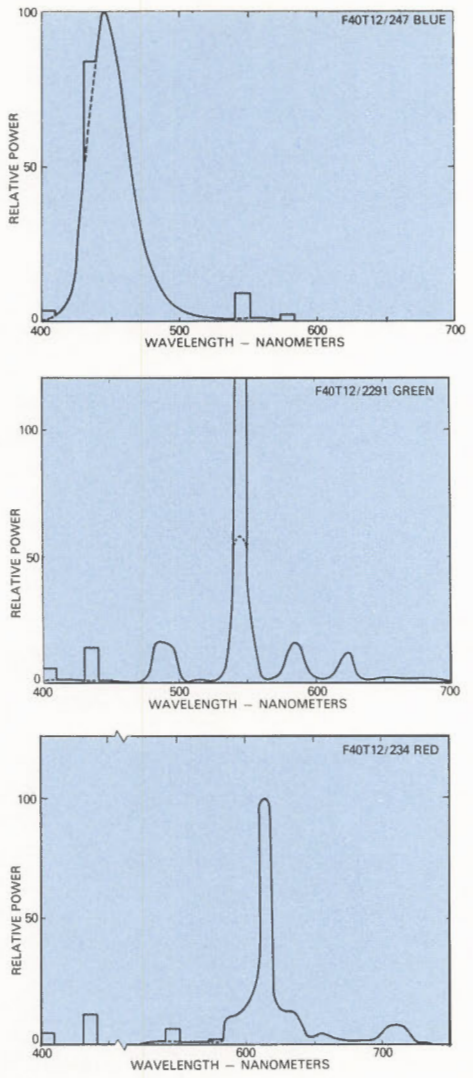


Figure 3.1-9 Spectral power distributions of typical narrow-band colored fluorescent lamps.

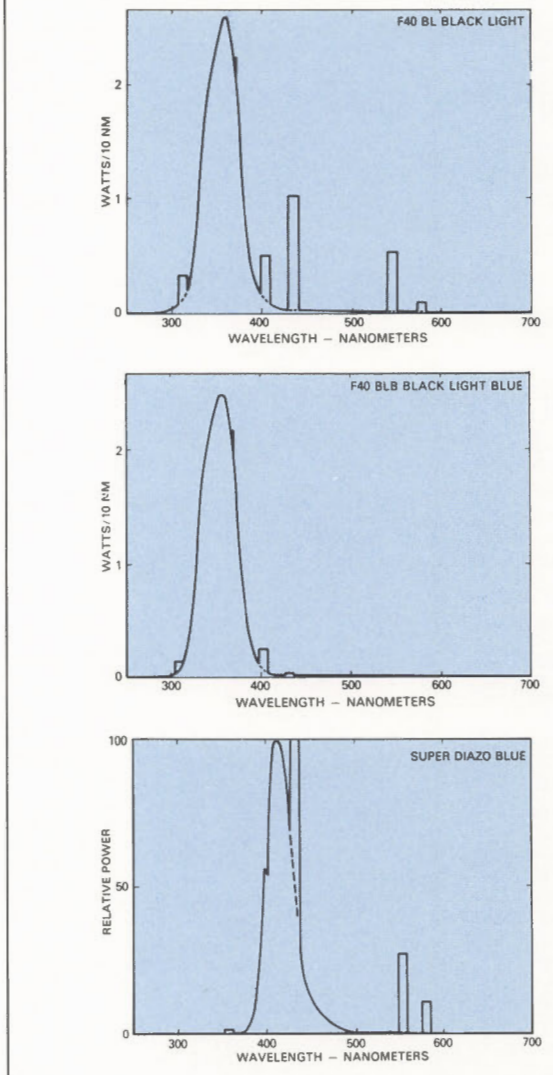


Figure 3.1-10 Spectral power-distributions of typical fluorescent lamps for photo-chemical activation.

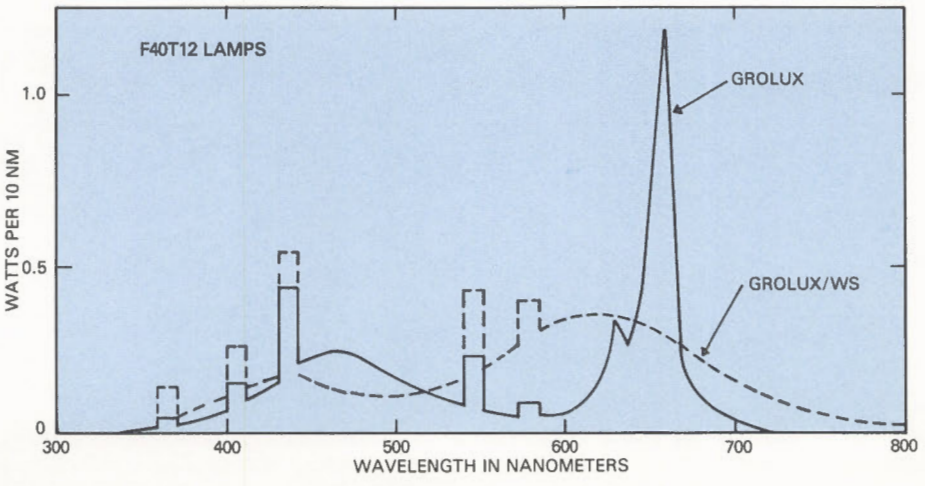


Figure 3.1-11 Spectral power distributions of fluorescent lamps for plant growth.

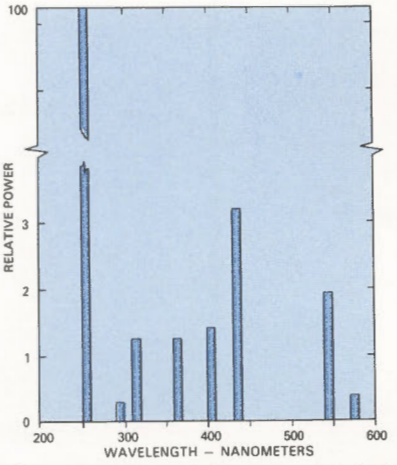


Figure 3.1-12 Spectral power distribution of G30T8 germicidal lamp.

ure 3.1-10 (photochemical activation lamps), Figure 3.1-11 (plant-growth lamps), and Figure 3.1-12 (G30T8 Germicidal Lamp). Germicidal lamps are actinic lamps but not fluorescent lamps, because they do not use an intermediate phosphor coating but radiate the mercury spectral lines directly. Since most glasses are opaque at wavelengths below about 300nm, germicidal lamp bulbs are made of special glasses that transmit well at shorter wavelengths. The blacklight-blue lamp of Figure 3.1-10 also employs a special glass which transmits in the UV but is an opaque blue in the visible.

Polar Intensity Distribution

The intensity of fully-coated linear tubular fluorescent lamps is essentially constant in each plane transverse to the axis of the lamp, but is slightly higher at the mid plane than in the end planes. The intensity in any plane through the centerline resembles a cosine function but decreases somewhat more rapidly at angles approaching 90° from the normal to the centerline. The approximate relation between normal intensity (i.e., at right angles to the lamp axis) and lamp flux is given by:

$\phi = 9.25 I_o$, where (eq. 3.1-2)

ϕ = flux in lumens
I_o = normal intensity

Designers should note that fluorescent lamps are optically dense, and it is not possible to direct appreciable flux through a fluorescent lamp by means of reflectors.

Reflector lamps modify the intensity in planes transverse to the axis by means of a translucent white reflective coating applied over a portion of the inner surface of the bulb before the phosphor is applied. The reflective coatings now used subtend central angles of 135° or 235°. Figure 3.1-13 shows the construction and intensity distributions of 135° and 235° reflector lamps. The luminance of the phosphor-coated window strip is significantly greater than that of a conventional fluorescent lamp because the phosphor not only produces light by its own fluorescence, but transmits part of the light directed to it by the reflective coating. However, the total lumen output of reflector lamps is a few per cent less than that of conventional unreflectorized fluorescent lamps coated with the same phosphor.

Aperture lamps are similar to reflector lamps, but both the reflective coatings and the phosphors are applied over portions subtending central angles of 300° or 330°, leaving a 60° or 30° window or aperture strip completely uncoated. The reflective coating is denser than that in reflector lamps to increase the reflectance and decrease losses to the rear. The luminance of the aperture may be up to six times that of a conventional fluorescent lamp fully coated with the same phosphor and is an inverse function of aperture angle; however, the total lumen output of the aperture lamp is less. Figure 3.1-14 shows the construction and intensity distributions of 30° and 60° aperture lamps.

For optical design purposes, the aperture may be replaced by a flat lambertian strip of the same length, width, and luminance.

Flicker and Stroboscopic Effects

Flicker Fluorescent lamps operating on ac will have cyclical variations of light output at twice the line frequency because the ultraviolet energy generated by the mercury arc discharge is a function of the instantaneous input power and thus varies between zero (when the arc is extinguished) and some maximum value (during the time the arc is ignited) at twice the line frequency (e.g., 120Hz on 60Hz lines). This double-frequency variation of the ultraviolet energy causes a corresponding double-frequency variation, called flicker, in the light produced by the phosphor. The light output does not fall to zero when the arc is extinguished because the phosphors used in fluorescent lamps produce light not only by fluorescence (i.e., as a result of, and only during the absorption of ultraviolet radiation from the mercury arc), but also by phosphorescence (i.e., as a result of the absorption of ultraviolet radiation from the mercury arc, and continuing for a noticeable length of time after excitation). This phosphorescent 'carry-over' continues to produce some light even at those times when the arc is extinguished.

Stroboscopic effect. The 120Hz flicker frequency resulting from operation on 60Hz lines exceeds the flicker fusion frequency, and therefore is usually not noticeable except by its stroboscopic effect on moving objects. The stroboscopic effect, which may be objectionable in some applications, increases with the amount of flicker so that it is necessary to have a reliable standard measure of the amount of flicker produced by a lamp.

Flicker index is the presently accepted measure of the amount of double-frequency variation in light output from lamps operating at specified line frequencies. Figure 3.1-15 shows how the flicker index for a lamp is obtained from the curve of instantaneous light output of that lamp during one power cycle. It is first necessary to determine the value of average light output, the area (Area 1) above the average value, and the area (Area 2) below the average value. The flicker index is then calculated by dividing the area (Area 1) above the average value by the total area (Area 1 + Area 2) under the curve. Flicker index, which takes the waveform of the light output into account, is a more reliable measure of flicker than the earlier-used per cent flicker, which is based only on maximum and minimum values of light output.

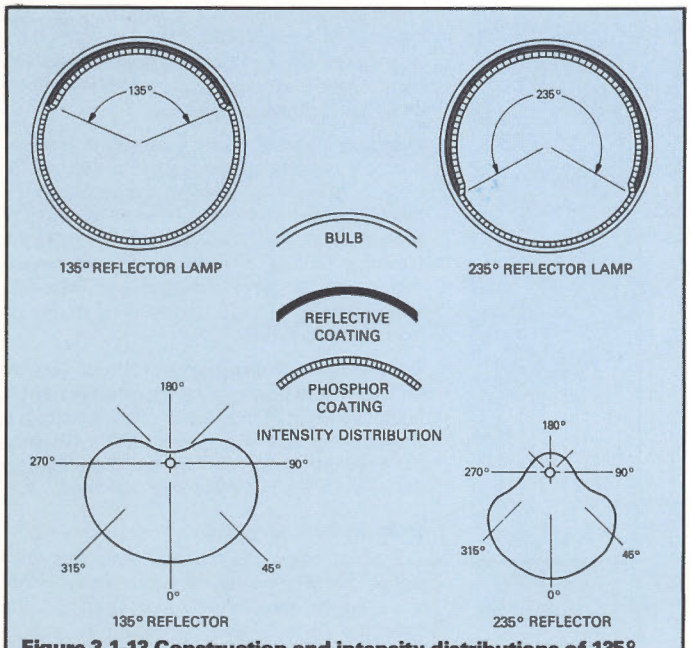


Figure 3.1-13 Construction and intensity distributions of 135° and 235° reflector lamps.

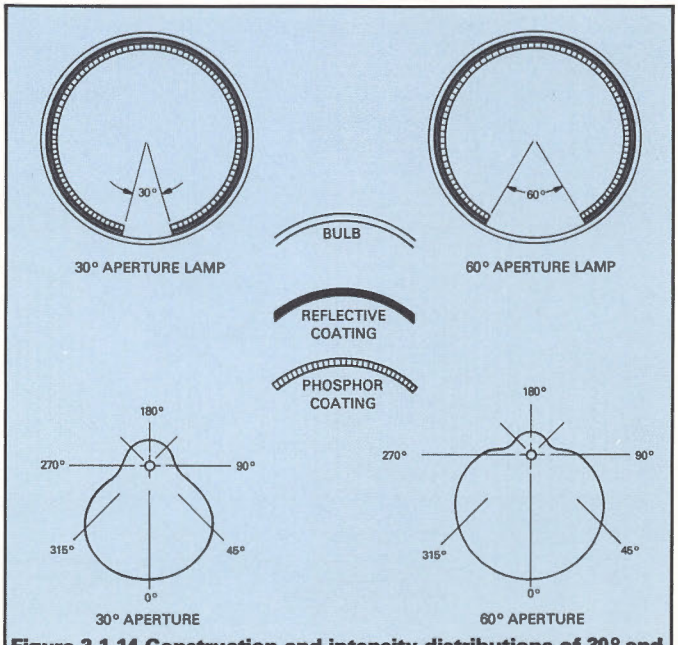


Figure 3.1-14 Construction and intensity distributions of 30° and 60° aperture lamps.

Operation of Fluorescent Lamps

Operating Circuits

Hot-cathode fluorescent lamps are categorized in terms of their starting characteristics as preheat, instant-start, and rapid-start types. Each type requires auxiliary components and circuits designed to match its starting and operating characteristics.

All arc-discharge lamps, including cold-cathode and hot-cathode fluorescent lamps, require starting voltages that are usually significantly higher than their operating voltages. The starting voltages of cold-cathode lamps are usually much higher than those of hot-cathode lamps. For example, the F40T12, a typical 40W hot-cathode fluorescent lamp, has an operating voltage of 102Vac, but requires a starting voltage of about 200 Vac (about 280V peak) if the cathodes are heated to emission temperatures (above 1223K) before the starting voltage is applied. The lamp may even be started with the cathodes cold, if the starting voltage is increased to about 385Vac (about 539V peak).

All arc-discharge lamps, including fluorescent lamps, also require a means for limiting the lamp current, because they operate in a region where the arc has negative resistance. The lamp current will 'run away' if not limited, e.g., by a positive dynamic impedance in series with the lamp.

The starting voltages and current-limiting impedances required by all fluorescent lamps, as well as the cathode-heating voltages required by hot-cathode fluorescent lamps, are provided by auxiliary electrical components called ballasts. These components are discussed below. Preheat fluorescent lamps require also auxiliary electrical components called starters, which are discussed under preheat lamp circuits.

Ballasts are designed to match the operating characteristics of specific fluorescent lamps operating in specific circuits at specific temperatures, voltages, and frequencies, and should not be used with other lamps or under other conditions.

Most ballasts contain inductive components, such as choke coils or autotransformers, which tend to reduce the power factor of the current drawn from the line by the lamp operating circuit. Some transformer-type ballasts and all choke ballasts are low-power-factor (LPF) types having power factors as low as 45%. The overall lamp circuit power factor can be increased to 90% or more, and the line current can be greatly reduced, by the use of high-power-factor (HPF) ballasts containing power-factor-correcting capacitors.

Because of losses within ballasts, they consume a small amount of power which must be added to the lamp wattage to obtain the total wattage of the lighting equipment. Special low-loss ballasts are available from most ballast manufacturers.

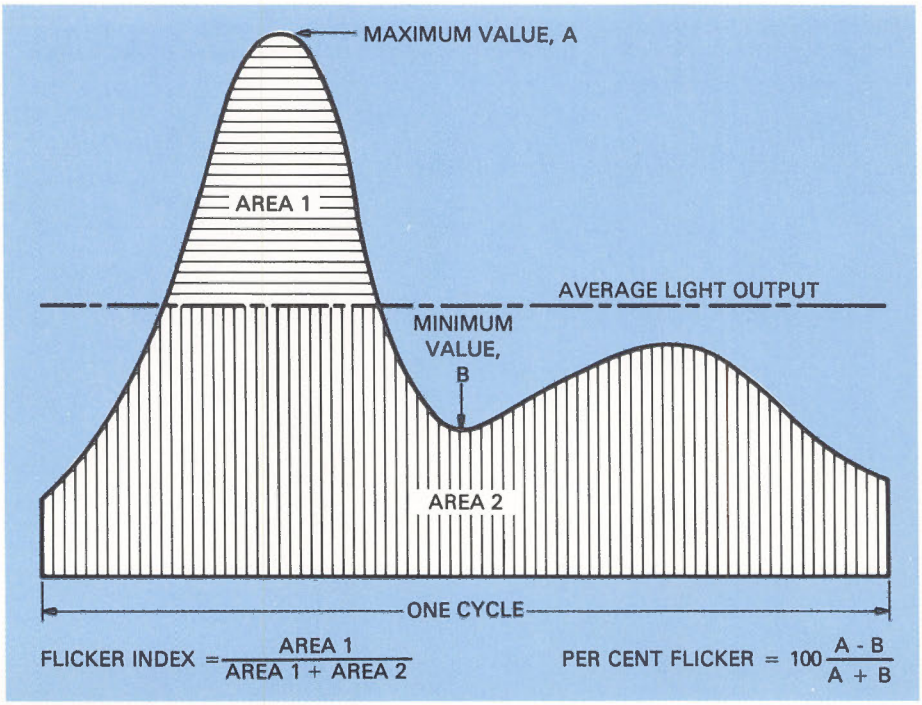

MAXIMUM VALUE, A
AREA 1
AVERAGE LIGHT OUTPUT
MINIMUM VALUE, B
AREA 2
ONE CYCLE
FLICKER INDEX = AREA 1 / (AREA 1 + AREA 2)
PER CENT FLICKER = 100 (A - B) / (A + B)

Figure 3.1-15 Method of determining flicker index and per cent flicker of a lamp from a plot of the instantaneous light output measured over one power-line cycle.

In order to reduce shock hazard, fixtures and ballasts should be grounded in accordance with the National Electric Code.

Grounding may also be required for starting. Most rapid-start lamps require a starting-voltage aid between the full length of the lamp and a grounded metal surface. For reliable starting, lamps rated at 0.5A or less must be mounted within one-half inch of the grounded metal surface. Lamps of higher ratings may be mounted within one inch of the starting aid. Properly grounded lamp fixtures will function as the required starting aids.

All ballasts produce a humming sound which varies with the type of ballast from a nearly inaudible sound to a rather noticeable noise. Most manufacturers give their ballasts sound ratings from A to F, to aid in selection. An A ballast usually has the least hum and should be used in quiet areas, such as study halls and homes. The most audible hum is produced by an F ballast which should be satisfactory for street lighting and noisy factory areas.

Class P ballasts, meeting Underwriters' Laboratories requirements, contain thermal protectors designed to disconnect the ballast from the circuit when the ballast case temperature reaches about 110°C for any period of time under abnormal conditions. After the ballast has cooled, if the resetting type protector is used, it recloses and the lamp relights.

Inverter ballasts. Sometimes it is desirable to convert direct current to alternating current for using fluorescent lamps in battery-powered equipment such as automobiles, boats, campers, hand lanterns, and in other mobile or portable applications. This can be done with an inverter ballast, which is a compact, solid-state device that converts low-voltage dc to high-frequency ac. Its use opens up a field to fluorescent lamps that was formerly reserved exclusively for incandescent lamps.

Flashing ballasts. When fluorescent lamps on ordinary ballasts are switched on and off frequently, the life is reduced. However, special flashing ballasts permit rapid-start lamps to be flashed millions of times in special applications. Flashing ballasts provide continuous heating current for the lamp cathodes even when the lamp is turned off, so that flashing opens the lamp arc circuit only.

Dimming ballasts are similar to flashing ballasts in that they provide continuous cathode heating current of the proper value regardless of the extent of dimming. However, they also supply a peaked starting voltage which permits the lamps to be started even when dimmed.

Preheat lamp circuits

Preheat lamps require separate starters which supply current through the cathodes to preheat them for the few seconds from turn-on to the time the lamp lights. Preheating causes the cathodes to emit electrons that permit striking the arc at a lower voltage. When the preheating

current is cut off abruptly, a high-voltage spike is generated which ignites the lamp. During normal lamp operation the cathodes are heated by the arc discharge. Figure 3.1-16 shows manual-starting and automatic-starting single-lamp preheat circuits, and Figure 3.1-17 shows an automatic-starting two-lamp preheat circuit.

The manual-starting single-lamp preheat circuit of Figure 3.1-16a, commonly used in desk lamps, has a normally-open pushbutton switch (labeled ON) and a normally-closed pushbutton switch (labeled OFF). The lamp is turned on by depressing the ON button for about one second, and then releasing it. During the time the switch is closed, current flows throught the ballast and through both cathodes, heating the cathodes to the temperature of emission. When the ON button is released, the starting current through the ballast and cathodes is interrupted, and the ballast develops an inductive pulse which strikes the arc. The lamp is turned off simply by depressing the OFF button to interrupt the current through the lamp. Note that this method can be extended to two-lamp manual-start preheat circuits.

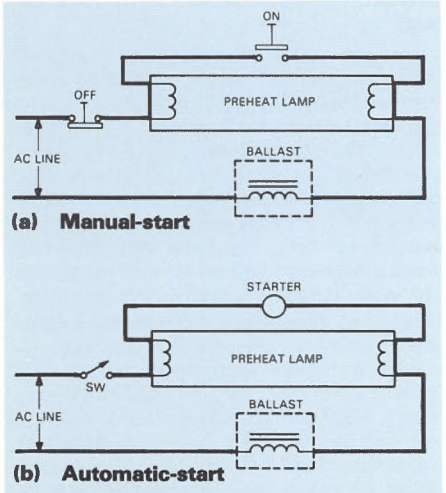


Figure 3.1-16 Single-lamp preheat circuits.

The automatic-starting single-lamp preheat circuit of Figure 3.1-16b uses a thermal-switch starter or a glow-switch starter, both of which are essentially delayed-action switches that are actuated by the current through the circuit when line switch SW is closed. Thermal starters open about one second after power is applied, interrupting the current through the ballast, which produces the inductive pulse that strikes the arc. The starters then remain open until the lamp is turned off. Glow-switch starters permit lamps to be turned on again immediately after turn-off, while thermal-switch starters necessitate a short delay. If a lamp does not light the first time an automatic starter opens, the starter will keep cycling until the lamp turns on. When a lamp reaches the end of its life it will not turn on at all, and the starter will keep cycling and flashing the cathodes until the lamp is replaced, the starter fails, or the ballast becomes overheated and opens. This phenomenon can be prevented by a manual-reset starter, which remains open after several attempts to start the lamp. This protects the starter and ballast, and prevents the annoyance of a continuously-flashing lamp. When the failed lamp is replaced, the starter is restored to normal operation by depressing the reset button. Manual reset starters have the disadvantage that the protector may open under conditions of low line voltage and high humidity, even though their lamps are operational. They will then remain open until manually reset. This disadvantage is overcome by automatic-reset starters, which remain open on lamp failure but which reset themselves after power is turned off.

The single-lamp preheat circuits of Figure 3.1-16 have low power factor because of the inductance of the ballast. Power factor can be improved in a number of ways, usually by the addition of capacitance.

The two-lamp preheat circuit of Figure 3.1-17 employs a lead-lag ballast which (through a choke) feeds lagging current to one lamp and (through a choke and capacitor in series) feeds leading current to the other lamp. The combination of leading and lagging currents increases the overall power factor of the current drawn from the line to 90% or higher. Also, since the lamps operate out of phase with each other, the cyclic variations of their light outputs are out of phase, and stroboscopic effect is greatly reduced.

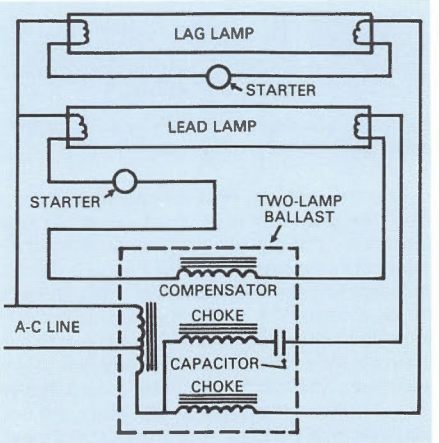


Figure 3.1-17 Two-lamp lead-lag preheat circuit.

The starting compensator in series with the lead lamp starter in Figure 3.1-17 is an additional choke coil that insures normal life for the lead lamp. With lamps of from 15W to 40W, the starting current should be considerably greater than the operating current, but the combination of the capacitor in series with the choke coil in the lead lamp circuit acts as an almost constant-current device which does not permit enough lead current to flow for easy starting. The compensator upsets the balance of the lead circuit and permits more current to flow, but only during the preheat period when the lamp is starting. Compensators are often omitted in low-cost ballasts, and are not required with 90W lamps.

Instant-Start Circuits

If enough voltage is applied across a fluorescent lamp, the arc will strike even if the cathodes are cold. Since no preheating time is required, a circuit with such a high voltage is called an instant-start circuit. Because a coil-heating circuit is not required, instant-start lamps have either a single-pin base at each end or bipin bases with the pins at each end internally connected together.

Instant-start lampholders incorporate switches to eliminate shock hazards. In order to insert a lamp into the lampholders, it must first be pushed into the spring lampholder at the high-voltage end and then inserted into the rigid lampholder at the low-voltage end.The base pins of the lamp break the circuit to the ballast when the lamp is removed, as shown in Figures 3.1-18 and 3.1-19.

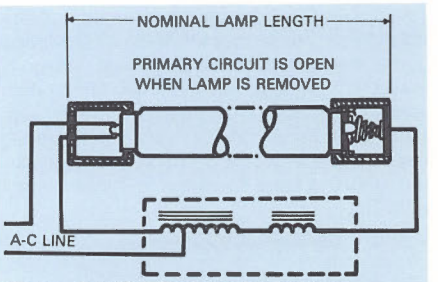


Figure 3.1-18 Slimline single-lamp instant- start circuit.

Most instant-start lamps are operated with series-sequence ballasts in the circuit shown in Figure 3.1-19. The series-sequence ballast is smaller, lighter, quieter, less expensive and more efficient than the lead-lag ballast. The two lamps are actually started in sequence a few thousandths of a second apart and operate in series.

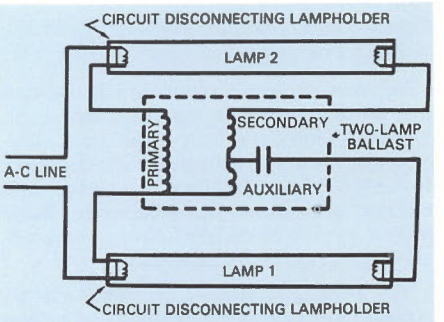


Figure 3.1-19 Typical two-lamp series-sequence instant-start circuit.

In Figure 3.1-19 it will be noted that the auxiliary winding supplies the voltage to start lamp 1. Before the first lamp lights, the voltage of the auxiliary winding subtracts from the primary and secondary voltages, resulting in insufficient starting voltage for lamp 2. However, when lamp 1 lights, the current flow through the capacitor shifts the phase relationship between the auxiliary winding and the secondary winding, causing the two voltages to add, and the sum of those voltages is sufficient to start lamp 2. The lamps then operate in series, with the auxiliary winding contributing nothing to the circuit.

Rapid-Start Circuits

Ballasts for rapid-start circuits have separate windings to provide continuous heating voltages for the lamp cathodes as shown in Figure 3.1-20. Unlike the preheat circuit which has no cathode heating after the arc strikes, the rapid-start circuit provides the lamp with a small heating current even when the lamp is burning. Under normal conditions, the rapid-start ballast will start the lamps in less than one second.

Two-lamp rapid-start series-sequence ballasts start the lamps in sequence and then operate them in series. After the circuit is turned on, the first operation is the heating of the cathodes to aid in starting the lamps by reducing the starting-voltage requirements. The capacitor across lamp 2 aids in starting lamp 1 first by momentarily applying nearly all of the ballast secondary voltage across lamp 1. Since the voltage drop across this lamp after starting is very low, practically all the ballast voltage is available to start lamp 2. The two lamps then operate with rapidly increasing current until stable operation at rated current is achieved. It is essential that proper cathode heat be maintained during lamp operation to insure normal lamp life.

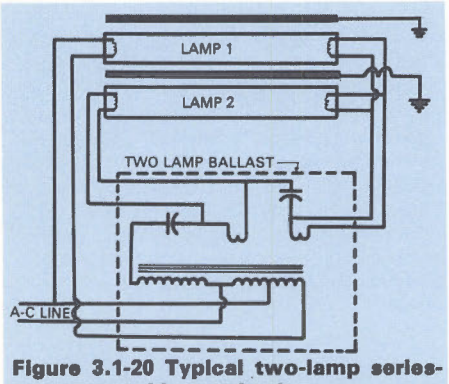


Figure 3.1-20 Typical two-lamp series-sequence rapid-start circuit.

To assure dependable starting, it is important that lamps operated on rapid-start ballasts be mounted within one inch of an electrically-grounded metal strip extending the full length of the lamp for HO an VHO lamps, and within one-half inch for lamps with operating current below 500mA. In most cases, the reflector or the wiring channel serves this purpose.

The dimming of rapid-start fluorescent lamps is practical when they are operated on dimming ballasts in specified dimming circuits. Dimming ballasts keep the lamp cathodes supplied with the proper heating current regardless of the extent to which the lamps may be dimmed. The dimming element that controls the lamp current may be either a variable voltage auto-transformer, adjustable reactor, thyratron, silicon-controlled rectifier or other solid-state device. Some dimming systems offer smooth control without flicker from full brightness to nearly total darkness with a dimming ratio of approximately 500 to 1. Lamp life is not usually affected by proper dimming service.

Trigger Start Circuits

The trigger-start circuit is sometimes used for operating preheat fluorescent lamps up to 20 watts in size that have high-resistance cathodes. This circuit was developed prior to the rapid-start circuit and is quite similar in that it provides a continuous heating of the cathodes and does not require a starter. The rapid-start circuit was introduced to minimize the power loss of the cathodes during lamp operation.

Direct Current Operation

Fluorescent lamps can be operated on direct current if a resistance of the proper value is used in series with an inductive starting choke to generate the starting-voltage pulse. A single-lamp dc circuit is shown in Figure 3.1-21. The choke type of ballast must be used even in the dc circuit to supply the inductive kick needed to start the lamp when the starting switch is opened. Since the choke has no limiting effect on the direct current flowing through the arc, a resistance must be used in series with the lamp and choke to limit the current. The value of resistance depends on the size of the lamp and the circuit voltage. The efficacy is reduced, as compared with alternating-current operation, because the resistance consumes approximately as much energy as the lamp. Lamp life will also be less.

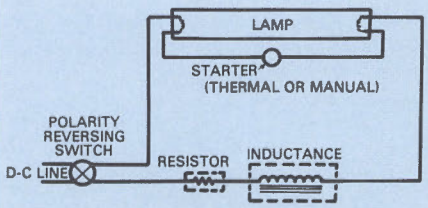


Figure 3.1-21 Circuit for direct-current operation of fluorescent lamps.

Another problem with dc operation results from the steady flow of direct current in one direction. This causes the mercury to drift toward the negative end of the tube. As a result the positive end becomes dim after several hours of operation. A polarity-reversing switch is recommended for most lamps, to reverse the connections to the electrodes every few hours and thus eliminate the tendency to burn dim at one end. For the shorter lamps, which are not troubled with mercury migration, it is a good idea to use a reversing switch to equalize the wear on the cathodes by reversing the direction of the current. The control switch should be the type that will automatically reverse the current each time the lamp is turned on.

Operating Characteristics

Effects of Voltage Variations. Fluorescent lamp circuits are sensitive to voltage changes, hence the voltage at the fixture should be kept within the rating specified on the ballast label. Voltages higher or lower than rated voltage will shorten life and reduce efficiency. Low voltage may also cause starting difficulties. Fluorescent lamps subjected to large drops in line voltage may go out momentarily or for longer periods, depending on the duration and amount of the voltage reduction, the lamp type, and the characteristics of the ballast. Approximate drops in voltage that will cause 40W T12 lamps to go out are as follows: preheat, 25%; rapid-start series-sequence, 20%; instant-start series-sequence, 50%; instant-start lead-lag, 40%.

The effect of variations in line volts on lamp volts, amperes, watts and lumens is shown in Figure 3.1-22 for a typical two-lamp series-sequence rapid-start circuit. From the curves it can be seen that 1% variation in the line voltage changes the lumen output only about 1%.

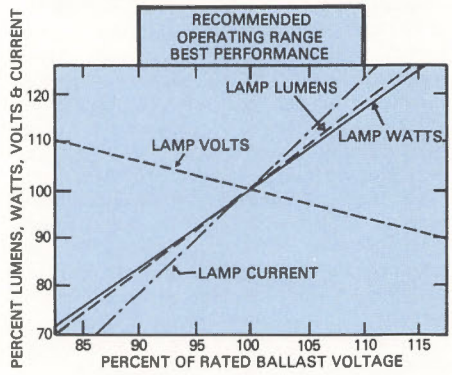


Figure 3.1-22 Effect of line voltage on lamp volts, amperes, watts, and lumens with a two-lamp series-sequence rapid-start ballast.

Low line voltage in preheat lamp circuits will reduce the preheat current, which may cause frequent flashing of the lamps during starting and shorten lamp life by driving the emissive material from the cathodes. Rapid-start lamps operated at low voltage will also have reduced cathode heater current which can adversely affect starting, increase early end discoloration, and shorten lamp life. Note that rapid-start lamps must have adequate cathode voltage not only when starting but even during operation.

Effects of Frequency Variations. Ballasts should always be operated at their design frequency. If a 60Hz lead-lag ballast, for example, is used on a 50Hz circuit, the current to the lag lamp is increased. This causes shorter lamp life and may overheat the ballast. A frequency higher than that for which the ballast was designed will reduce the current to the lag lamp. These changes in frequency have opposite effects on lead lamps.

The efficacy and light output of most fluorescent lamps increase with frequency. Therefore some fluorescent lamp installations are designed to operate at frequencies higher than 60Hz,

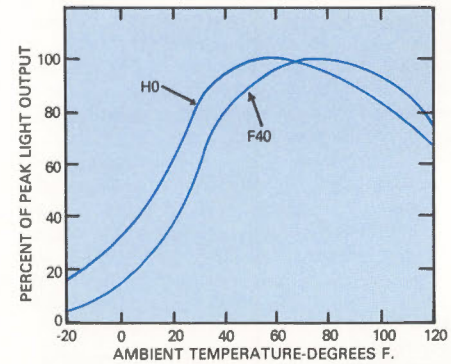


Figure 3.1-23 Light output versus ambient temperature for bare fluorescent lamps in still air.

such as 400Hz, 840Hz, or even higher. These use special ballasts which are smaller and usually have lower wattage losses than 60Hz ballasts. Installations of high-frequency systems are limited primarily by the cost and efficiency of the equipment required to convert 60Hz power into higher frequencies. Some present high-frequency systems use centralized static-converter power supplies and operate at frequencies of 3000Hz or more.

Effects of Temperature. The light output of a fluorescent lamp varies considerably with the temperature of the bulb wall because the temperature of the coolest point on the bulb wall determines the mercury vapor pressure, which affects the light output of the lamp. Since changes in ambient temperature are accompanied by similar changes in bulb wall temperature, the light output is affected by variations in ambient temperature as shown in Figure 3.1-23. Rated lumen output values are usually measured at a standard industry test ambient temperature of 77°F (25°C).

Fluorescent lamps used indoors at normal room temperature provide the most light when they are operated in lighting equipment designed to prevent overheating. Figure 3.1-23 shows that the light output decreases as the ambient temperature increases above 77°F (25°C). Heat-removal air-handling troffers improve light output by cooling the lamps. Note, however, that fluorescent lamps exposed to excessive cooling from air conditioning may have reduced light output.

When fluorescent lamps are used outdoors, starting may be a problem at low temperatures, and higher starting voltages may be required. Standard ballasts will start lamps reliably at temperatures down to 50°F (10°C), and low-temperature ballasts are available to provide starting down to 0°F (-17.8°C) or even -20°F (-28.9°C).

Selection of lamps for outdoor applications is critical, because the light output depends on the bulb temperature which varies with lamp type and with ambient temperature. Curves of relative light output versus ambient temperature for several types of fluorescent lamps commonly used out-doors are shown in Figure 3.1-24. The temperature at which peak light output occurs depends on the lamp, the design of the fixture, and wind speed.

Effects of Humidity. Maximum effectiveness of the grounded metal starting aid occurs only when the bulb is dry. High humidity can produce a film of moisture on the bulb which has sufficient conductivity to shield the internal parts of the lamp from the starting aid and render it ineffective. To assure reliable starting under conditions of high humidity, rapid-start and instant-start lamps are coated with an outside silicone material. The silicone coating causes moisture to form in minute droplets instead of a continuous film, thus preventing the development of a shunting conductivity and ensuring reliable starting even when the humidity is high.

Lumen Maintenance. Since fluorescent lamp light output drops much more rapidly during the first 100 hours of life than it does later, the published 'initial lumens' is the value measured after the first 100 hours of burning. The drop-off is much more gradual during the remaining lamp life. During lamp life, normal internal darkening of the inner surface of the bulb will occur. This darkening will be greater at the lamp ends. The smaller-diameter lamps will show greater end-darkening because the cathodes are closer to the bulb wall. Lumen maintenance is not appreciably affected by the number of burning hours per start. The lumen maintenance is better with standard T12 rapid-start and slimline lamps than with high-output types. Also, some phosphors have better maintenance than others. Figure 3.1-25 shows lumen maintenance for three types of cool-white fluorescent lamps.

Life Expectancy. Fluorescent lamps have much longer rated lives than incandescent lamps, but the shape of the life expectancy curve is quite similar, as shown in Figure 3.1-26. Because of slight variations in lamp-making operations and lamp materials, it is impossible to have each lamp operate for exactly the life for which it was designed. For this reason, lamp life is rated as the average life of large groups of lamps operated under controlled laboratory conditions. Rated average life is the point at which approximately 50 per cent of the lamps in a large group have burned out and 50 per cent remain burning as pictured by the life expectancy curve.

During the starting cycle and operating period of a hot-cathode fluorescent lamp, the emissive material is gradually removed from the cathodes. The normal end of life is reached when there is insufficient emissive material remaining on either cathode to strike the arc. Since the published average rated life figures are generally based on a three-hour burning cycle, the ratings reflect the effects of both starting and burning. Any changes in the hours burned per cycle will affect life in service. Shorter burning cycles (more frequent starts) shorten life, and longer burning cycles (less frequent starts) increase life. Figure 3.1-27 shows typical mortality curves for the 40-watt rapid-start lamp on different burning cycles.

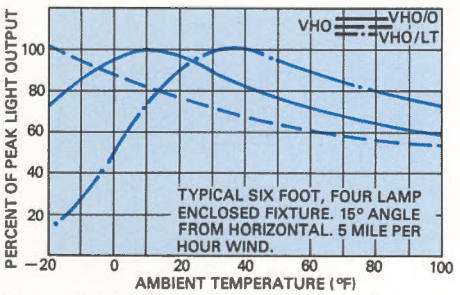


Figure 3.1-24 Light output versus ambient temperature for several types of outdoor fluorescent lamps.

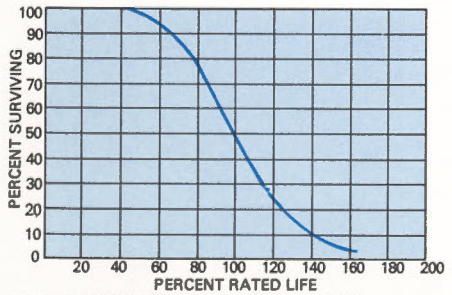


Figure 3.1-26 General pattern of life expectancy of fluorescent lamps.

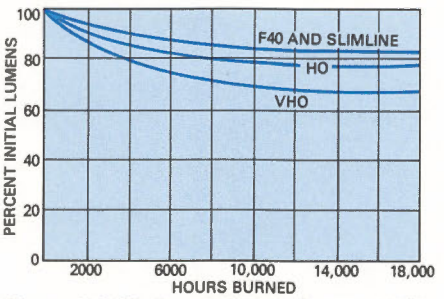


Figure 3.1-25 Approximate lumen maintenance of various types of cool-white fluorescent lamps.

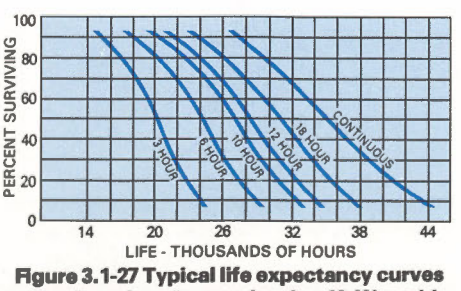


Figure 3.1-27 Typical life expectancy curves at various burning cycles for 40 W rapid-start lamps rated at 20,000 hours.

3.2 Low-Pressure Sodium Lamps

Low-pressure sodium lamps produce nearly-monochromatic yellow light at the sodium 'D' lines of 589.0 and 589.6 nm, with efficacies up to 185 lm/W. Such high efficacies are achieved because of the high efficiency of conversion of electrical energy into sodium resonance radiation which occurs at low densities and optimum sodium vapor pressures in the order of 0.003 torr (4×10^{-6} atm) and because of the high luminous efficacy of the yellow sodium resonance radiation. To achieve the optimum sodium vapor pressure, a cold spot temperature of about 260°C must be maintained and the arc tube must be enclosed within a tubular outer bulb or jacket. The arc tube contains a starting gas (e.g., neon plus small amounts of argon) to facilitate initiation of the discharge, and sufficient sodium to produce the desired vapor pressure and temperature. Arc-tube heat losses caused by conduction and convection are reduced by evacuating the jacket, and heat losses caused by radiation are reduced by applying to the inner wall of the jacket an indium-oxide coating that transmits light but reflects infrared radiation.

Construction

As shown in Figure 3.2-1, low-pressure sodium lamps are made in single-ended and double-ended versions.

Single-ended lamps have arc tubes bent into hairpin shapes or U-shapes with closely-spaced legs. The metal-oxide electrodes are designed to be heated to electron-emission temperatures by ion bombardment. Connections to the electrodes are made through a two-pin bayonet base at the seal end of the jacket. The parameters of these lamps are: wattages, 17 to 180W; jacket diameters, 2-1/8″ (T17); nominal lengths, 12-3/16″ to 44-1/8″; initial lumens, 4,650 to 32,000 lm.

Double-ended lamps have arc tubes dimpled at regular intervals. The electrodes are connected to medium-bipin bases at the ends of the jacket. Parameters are: wattages, 60 and 200W; jacket diameters, 1½″ (T12); nominal lengths, 16¼″ and 35¼″; initial lumens, 6,000 and 25,000 lm.

Spectral Power Distribution

The SPD of typical low-pressure sodium lamps is shown in Figure 3.2-2. Note that almost all of the output is in the 589nm region, and that there is very little background radiation at other wavelengths.

Spatial Distribution of Intensity

The arc is essentially opaque at its radiation wavelength. Consequently, the arc tube can be approximated as a lambertain surface for most optical design purposes. The intensity distribution from a bare lamp depends on the configuration of the arc tube, on the masking by the base and other components, etc. Figure 3.2-3 shows the typical intensity distribution of the single-ended lamps shown in Figure 3.2-1.

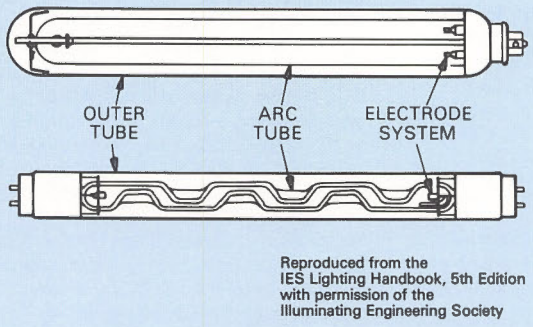


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Figure 3.2-1 Construction of single-ended and double-ended low-pressure sodium lamps.

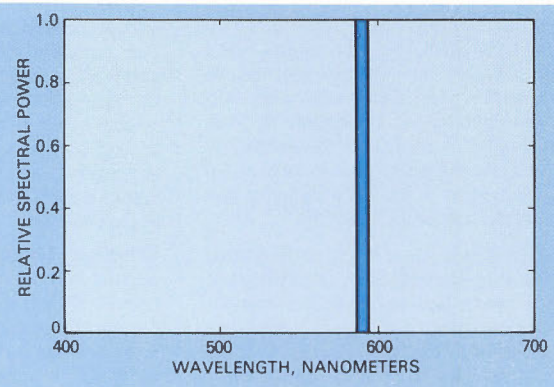


Figure 3.2-2 SPD of typical low-pressure sodium lamps.

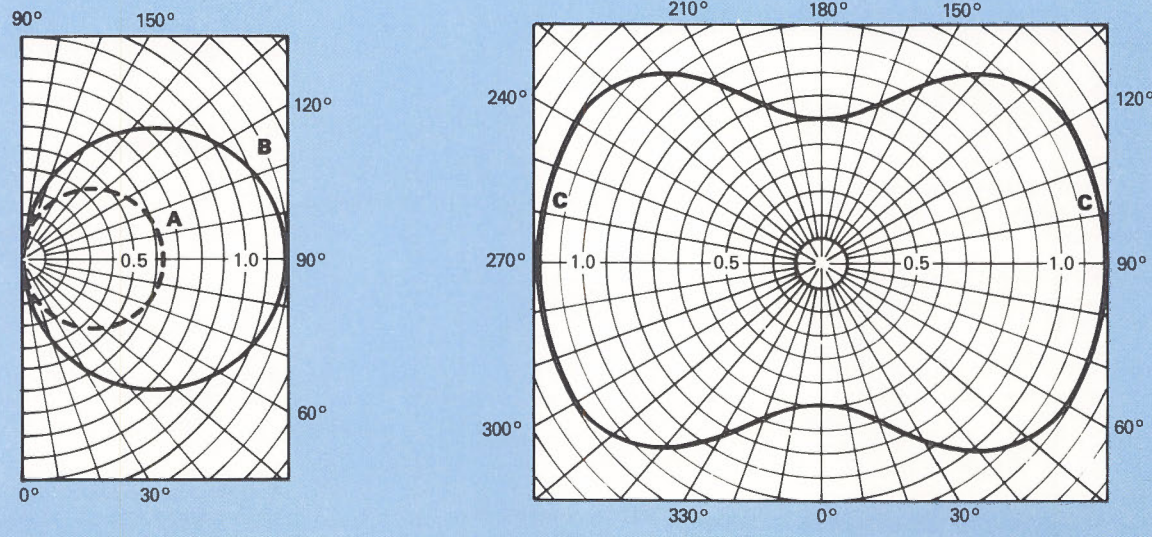


Figure 3.2-3 Relative polar intensity distributions of typical single-ended low-pressure sodium lamps. A - plane containing lamp axis and "U" arc tube; B - plane containing lamp axis and perpendicular to plane of "U" arc tube; C - plane perpendicular to lamp axis.

4.0 Medium Pressure Discharge Lamps

Medium-pressure discharge lamps, commonly called high-intensity discharge or HID lamps, operate at medium pressures in the range of 1 to 10 atmospheres, with loadings in the order of 50W/cm (125W/in) of arc length, and emit a small amount of continuous radiation in addition to spectral lines and/or bands.

Most HID lamps are 'jacketed'; i.e., they comprise small inner bulbs or arc tubes mounted inside glass outer bulbs or jackets to conserve heat and to prevent emission of ultraviolet radiation. The jackets are evacuated or filled with an inert gas to prevent oxidation of the hot lead seals of the arc tube. Jacketed HID lamps include mercury lamps (with uncoated jackets or with internally phosphor-coated jackets), metal-halide (e.g., Metalarc, Swingline, and Super Metalarc) lamps, and high-pressure sodium lamps.

Unjacketed tubular mercury and metal-halide (e.g., Brite-Line) HID lamps are also available; these are used mainly for reprographic and photochemical application where ultraviolet radiation is required.

Principles of Operation

Figure 4.1-1 shows the electrical circuit of a typical jacketed mercury HID lamp. The arc tube is filled with mercury vapor and with a small amount of argon. When line voltage is applied, the ballast impresses a starting voltage across the operating electrodes at the ends of the arc tube and also (through the starting resistor) across the small gap between the starting electrode and the adjacent operating electrode. This initiates across the starting gap an argon discharge, the current of which is limited by the starting resistor. When sufficient ionized argon from the starting discharge is distributed throughout the arc tube, the main discharge occurs between the operating electrodes. This discharge heats the operating electrodes, causing the emission of electrons and lowering the voltage across the arc, and also vaporizes all the mercury in the lamp. The amount of mercury in the arc tube determines the operating pressure, which is in the range of 2 to 4 atmospheres in most mercury HID lamps. When the main arc is struck, the starting discharge is extinguished because the starting resistor reduces the potential across the starting gap to less than the sustaining voltage of the starting discharge. Current then flows only in the main arc discharge between the operating electrodes, and the lamp quickly heats up to operating temperature.

The mercury arc discharge produces radiation mainly at the typical mercury spectral lines of 253.7, 334.2, 365.0, 404.7, 435.8, 546.1, 578.0nm, etc; but there is negligible radiation in the orange and red regions (590-760nm) of the spectrum. Because of the low orange and red content, the light output from the arc tube is a bluish white having a low color-rendering index. To increase the color-rendering index, phosphors may be applied to the inner surface of the outer bulb or jacket which contains the arc tube. These phosphors convert some of the ultraviolet radiation (mainly the 253.7nm line) into visible radiation in the orange and red regions of the spectrum. However, the phosphors have the incidental effect of transforming the lamp from a small source (the arc tube) of high luminance into a much larger source (the jacket) of lower luminance.

Physical Characteristics

Typical Construction of Jacketed Mercury HID Lamps

The fused-quartz arc tube shown in Figure 4.1-2 is firmly supported by means of spring spacers within a rigid, one-piece, 'rough-service frame mount', which in turn is positioned within the outer bulb by support rods extending through the glass press of the outer bulb.

Electrodes are connected through thin molybdenum ribbons in the ends of the arc tube. One operating electrode and a starting electrode are sealed into the end of the arc tube nearest the base of the lamp, and a second operating electrode is sealed into the other end. The starting electrode is a small rod or probe. Each operating electrode comprises a formed tungsten rod which supports a double-helix tungsten coil. A trimetallic oxide emissive compound, embedded within the turns of the coil, insures high electron emission and maximum lumen maintenance during the life of the lamp. The operating electrode at the base end of the lamp is connected to the center contact of the mogul screw base, and the operating electrode at the outer end is connected through the mounting frame to the shell of the base. The starting electrode is connected through the internal starting resistor to the base shell.

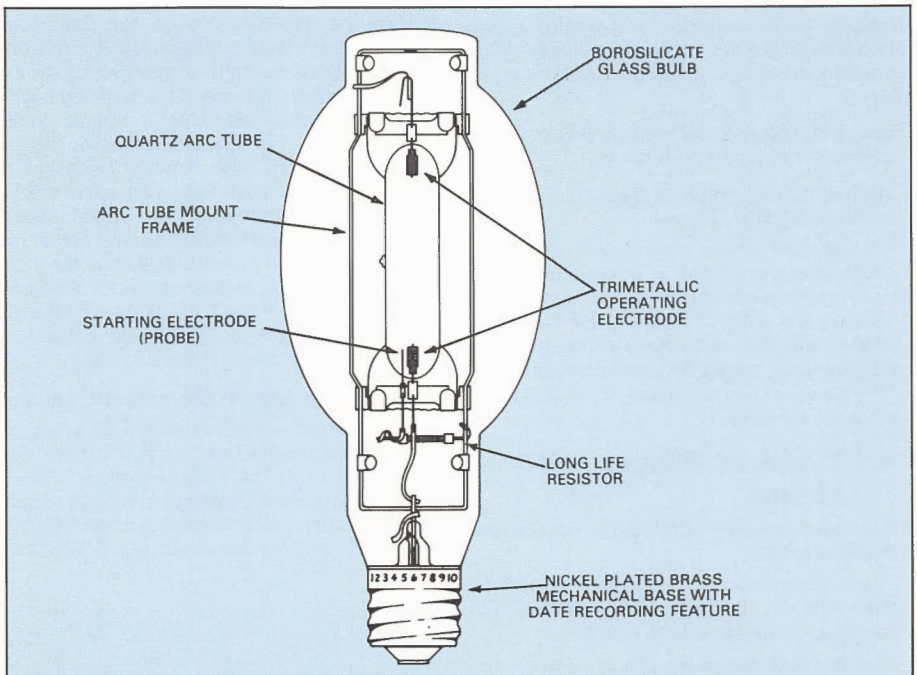

BOROSILICATE GLASS BULB
QUARTZ ARC TUBE
ARC TUBE MOUNT FRAME
TRIMETALLIC OPERATING ELECTRODE
STARTING ELECTRODE (PROBE)
LONG LIFE RESISTOR
1 2 3 4 5 6 7 8 9 10
NICKEL PLATED BRASS MECHANICAL BASE WITH DATE RECORDING FEATURE

Figure 4.1-2 Typical construction of jacketed mercury HID lamps.

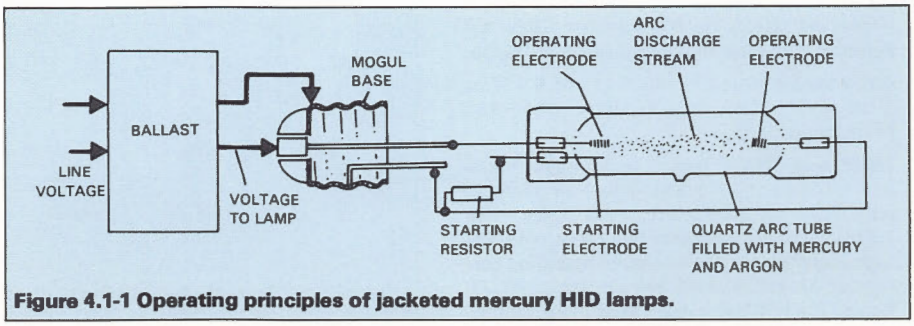


Figure 4.1-1 Operating principles of jacketed mercury HID lamps.

The arc-tube fill is mercury vapor and a small amount of argon gas. The mercury is usually condensed at room temperature but completely vaporizes at lamp operating temperature, building up to an operating pressure of 2-4 atmospheres.

The jacket, which conserves the heat of the arc tube and maintains it at a relatively constant operating temperature, is usually made of hard borosilicate glass which transmits down to about 300nm, but absorbs the 253.7nm ultraviolet line. Other glasses may be used for transmission in spectral regions outside the passband of borosilicate glass. Typical jacket bulbs for HID lamps are shown in Figure 4.1-3: B for bulbous, BT for tubular-bulbous, and R for reflector with the maximum diameter given in eighths of an inch.

Phosphor and/or metallic coatings may be applied to the inner surface of the jacket, to modify the spectral and/or spatial distribution of the light output.

The jacket fill is an inert gas, usually nitrogen, which prevents oxidation of the molybdenum lead seals of the arc tube and maintains a high breakdown voltage across the parts inside the jacket.

Bases of most jacketed mercury HID lamps are medium and mogul screw bases.

Typical Construction of Unjacketed Tubular Mercury HID lamps

Unjacketed tubular mercury HID lamps are similar to the arc tubes in jacketed lamps but have only two electrodes so that high starting voltages are required. Since these lamps are tubular, the main differences among them are bulb diameter, length, and base configurations. The bases shown in Figure 4.1-4 are those presently available.

4.1 Types of Mercury HID Lamps

Jacketed Mercury HID Lamps for General Applications

Jacketed mercury lamps for general applications range in size from 40W to 1000W. The following groupings can be made:

40W to 100W lamps have medium bases and A23, B21, or G40 bulbs. They are about the same size as conventional 150W incandescent lamps, but have up to 250 % the light output.

100W, 175W and 250W lamps have mogul bases and BT25 or BT28 bulbs. They are available with clear and phosphor-coated bulbs.

400W lamps have mogul bases and BT-37 or T-16 bulbs. They are available clear and phosphor coated.

700W and 1000W lamps have mogul bases and BT46 or BT56 bulbs. They are available with clear or phosphor-coated bulbs. The 1000W lamp is available in two types. The H34 high-current lamp has a nominal operating current of 8A and a rated average life of 16,000 hours. The H36 low-current lamp has a nominal operating current of 4A and a rated average life of 24,000 hours. They operate with different ballasts and are not interchangeable.

Self-ballasted lamps employ a tungsten filament as a ballast in series with the arc tube. The luminous efficacy of the filament is low to produce long life. These lamps are available in several wattages and bulb shapes for operation on 120V or on 220-240V without an external ballast. They have much lower efficacies and shorter lives than externally-ballasted mercury lamps. The RS sun lamp is a 275W self-ballasted lamp in a germicidal glass R-40 bulb with built-in reflector.

Mercury reflector lamps have three different kinds of reflector coatings; metallic, phosphor, and metallic-and-phosphor. The metallic coating reflects most of the light through the face of the bulb. The phosphor coating converts some of the ultraviolet energy from the arc tube into light and thus provides improved color; it reflects about two-thirds of the light through the face of the bulb and transmits some of the remaining one-third through the side of the bulb. The metallic-and-phosphor reflector coating develops light of improved color and reflects most of it through the face of the bulb. These lamps are available in various colors. Clear lamps give the characteristic mercury blue-green light that distorts most colors. Color-improved lamps have a phosphor coating that increases the red content of the output. Brite-white-deluxe lamps have better color rendition and higher lumen output than the color-improved lamps. Mercury reflector lamps are available in 100W to 400W ratings in PAR and R bulbs, and 1000W in a BT56 bulb; a variety of spot and flood distributions is available.

Unjacketed Tubular Mercury HID Lamps

Unjacketed tubular mercury HID lamps are available in the five basic configurations shown in Figure 4.1-4. The wattage range is 175W to 4000W, the corresponding arc voltage range is 135V to 1200V, and the loading range is 60W/in to 500W/in. Bulb diameters are 3/8″ (T3) to 1″ (T8) and the lighted lengths range from 1.5″ (MOL 3-¾″) to 24″ (MOL 27¼″). All designations have the prefix H (from Hg, the chemical symbol for mercury), followed by the nominal watts, bulb designation, lighted length, and base designation. Thus an H175T4/1½Q is an unjacketed tubular mercury HID lamp with a nominal rating of 175W, a T4 bulb (4/8″ or ½″ in diameter), 1.5″ lighted length, and a Q base.

Illumination Characteristics

Initial lumen outputs of jacketed mercury lamps at 100 hours of operation range from about 1250 lm for 40W ratings to about 60,000 lm for 1000W ratings.

Initial efficacies range from 29-34 lm/W for 40W lamps of various colors, to 55-63 lm/W for 1000W lamps of various colors. These efficacies do not include ballast losses which should be added to the lamp watts when making comparisons with other light sources.

Spectral power distribution and color temperature. The mercury arc discharge produces radiation at the typical mercury spectral lines of 184.9, 253.7, 312.9, 365.4, 404.7, 435.8, 546.1, 578.0nm, etc. Fused-quartz arc tubes in jacketed lamps transmit all of these lines, but the hard borosilicate jacket transmits only the 312.9nm line and longer-wavelength lines. These lines are shown in Figure 4.1-5a, which is the spectral power distribution in 10nm bands of 400W clear mercury lamps. Figures 4.1-5b, c, and d, are spectral power distributions of 400W mercury lamps with color-improved, warm-deluxe, and brite-white-deluxe phosphor coatings respectively. The color characteristics of these four lamps are listed in Figure 4.1-6.

The spectral power distribution of light from unjacketed mercury HID lamps is similar to that from the arc tubes of jacketed lamps, except that the unjacketed lamps are made of special fused quartz which absorbs radiation in the ozone-generating region below 200nm. Figure 4.1-7 shows the spectral power distribution of typical unjacketed mercury HID lamps.

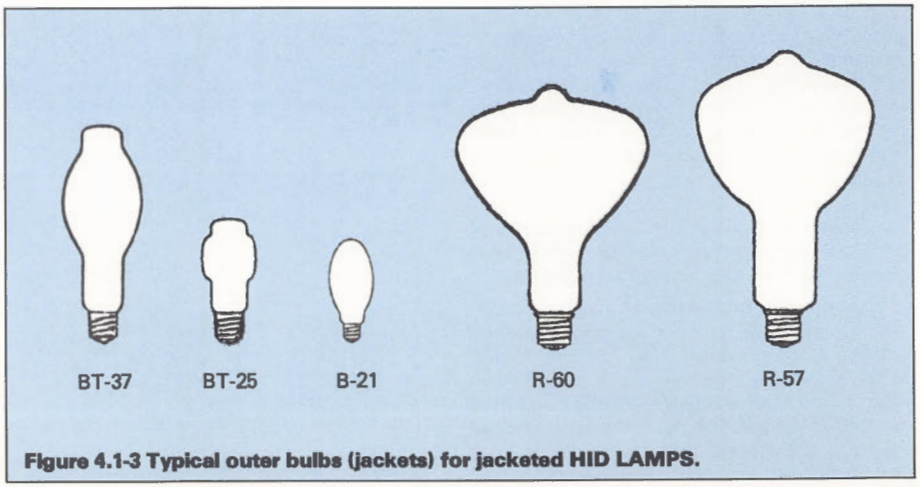


Figure 4.1-3 Typical outer bulbs (jackets) for jacketed HID LAMPS.

Although these unjacketed lamps have no ozone hazard, they transmit significant amounts of radiation in the 200-315nm erythemal region, so that eyes and skin must be protected from direct or reflected radiation from these lamps. Equipment must therefore be designed to prevent even momentary exposure of personnel to this erythemal radiation.

Operating Characteristics

Auxiliary components and circuits. Mercury HID lamps must be operated with ballasts designed to meet ANSI specifications. Such ballasts will provide both adequate starting voltage and current limiting during operation. Various types of ballasts are available for single-lamp and two-lamp operation.

Effects of line-voltage variation. As shown in Figure 4.1-8, the effects of line-voltage variations on mercury HID lamps depend on the characteristics of the ballast. Note that these lamps cannot be electrically dimmed without special dimming ballasts.

Lamp operating position. Light output ratings of jacketed mercury HID lamps are established for vertical operation, and sometimes for horizontal operations, because the lamp wattage, lumen output, and efficacy are usually lower for horizontal operation. Unjacketed mercury HID lamps should be operated horizontally with the exhaust tip up; U-shaped lamps may be operated with sides vertical only.

Effect of temperature. Unlike fluorescent lamps, the lumen output of jacketed mercury HID lamps during operation is not significantly affected by ambient temperatures because the jacket acts as a heat-conserving insulator for the arc tube. However, for satisfactory starting at low temperatures, ballasts supplying higher starting voltages are required.

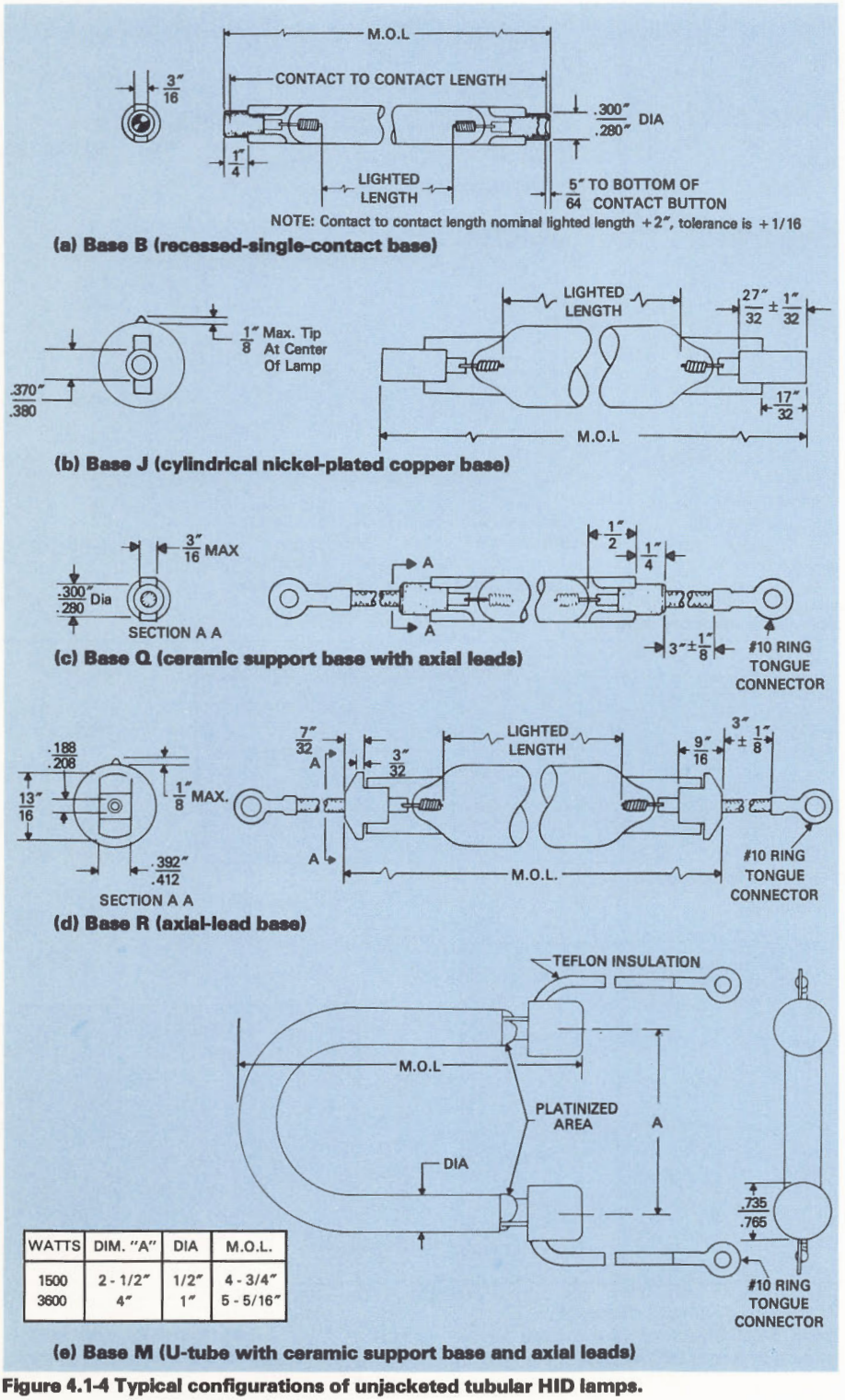
Excessive temperatures (Above 210°C on mogul screw bases or above 400°C on the jacket wall) may cause unsatisfactory performance or failure because of damage to the arc tube, jacket, or other parts of the lamp.

Recommended arc-tube-wall operating temperatures for unjacketed lamps are 650°C to 700°C at the center of the tube which is normally the hottest spot. The maximum allowable range is 600°C to 800°C. Since the lamps are not protected by an inert atmosphere, the molybdenum seals will oxidize and fracture at temperatures in excess of 350°C. Forced cooling may be required to maintain these wall and seal temperatures, and air switches should be incorporated to protect lamps in case of blower failure.

Restrike time. When a mercury lamp is turned off, it will not light again until it has cooled enough to lower the vapor pressure to the point at which the arc will restrike with the available starting voltage. At usual room temperatures and without an enclosing luminaire, the time from initial starting to full light output, and the restrike time of the hot lamp, range from 3 to 7 minutes for the various types of lamps.

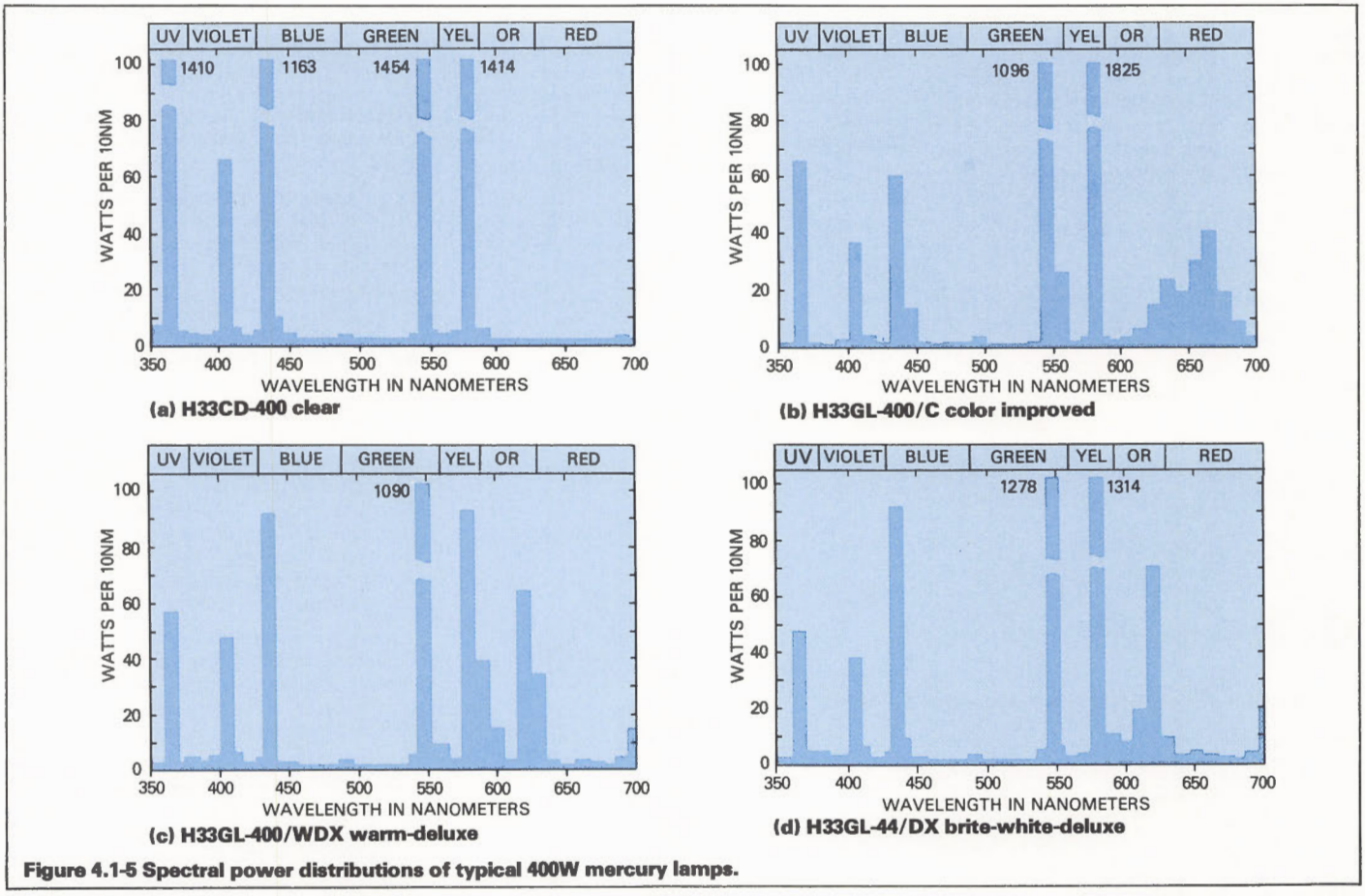
Lumen maintenance. The lumen output of jacketed mercury HID lamps decreases during life, mainly as a result of the deposition of tungsten and emissive materials from the electrodes on the arc tube walls. Initial lumens are rated at 100 hours of operation because 'clean-up' of impurities occurs during that time, with a resulting drop of as much as 10% in lumen output. After 100 hours, the lamps stabilize and the lumen output decreases slowly to the end of life.

Lumen maintenance is better for clear lamps than for phosphor-coated lamps of equal ratings, and is generally slightly better for vertical than for horizontal operation. Figures 4.1-9 and 4.1-10 show lumen maintenance for typical clear lamps operating vertically and horizontally.



WATTS	DIM. "A"	DIA	M.O.L.
1500	2 - 1/2"	1/2"	4 - 3/4"
3600	4"	1"	5 - 5/16"

Figure 4.1-4 Typical configurations of unjacketed tubular HID lamps.



(a) H33CD-400 clear

(b) H33GL-400/C color improved

(c) H33GL-400/WDX warm-deluxe

(d) H33GL-44/DX brite-white-deluxe

Figure 4.1-5 Spectral power distributions of typical 400W mercury lamps.

LAMP DESIGNATION	COLOR DESIGNATION	INITIAL EFFICACY LM/W	CIE CHROMATICITY X	CIE CHROMATICITY Y	CORRELATED COLOR TEMP. °K APPROX.	CIE COLOR-RENDERING INDEX
H 33 CD-400	CLEAR	50	.320	.379	5900	22
H 33 GL-400/C	COLOR-IMPROVED	50	.383	.419	4200	45
H 33 GL-400/WDX	WARM DELUXE	51	.400	.380	3600	47
H 33 GL-400/DX	BRITE-WHITE DELUXE	56	.382	.385	4000	43

Figure 4.1-6 Color characteristics of typical 400W mercury HID lamps.

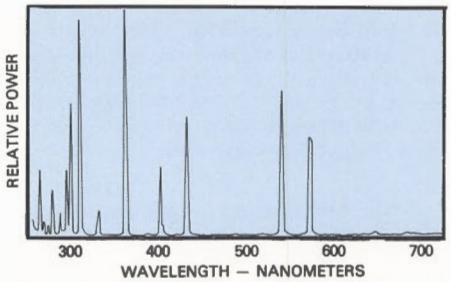


Figure 4.1-7 Spectral power distribution of an H-Series unjacketed mercury HID lamp with T3 bulb and 12-inch lighted length.

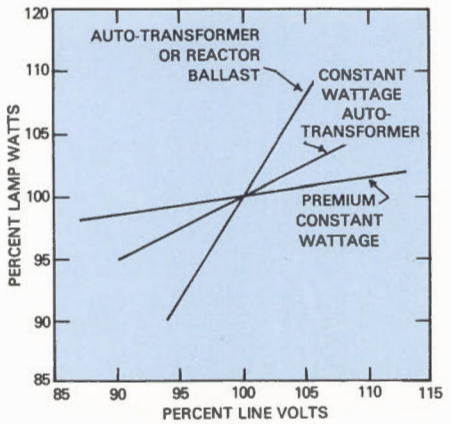


Figure 4.1-8 Effect of line-voltage variations on mercury HID lamps.

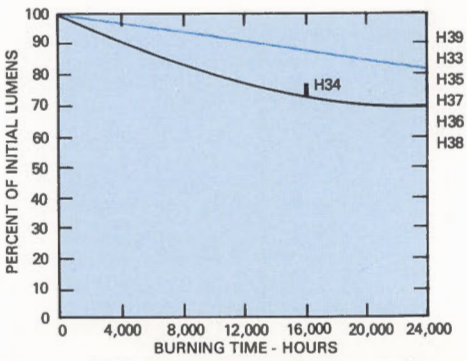


Figure 4.1-9 Approximate lumen maintenance of typical clear mercury lamps operating vertically.

Lamp life. Most jacketed mercury HID lamps with mogul bases have rated average life of 24,000 hours. Lamps with medium bases have rated average life of 10,000 to 16,000 hours. Figure 4.1-11 shows typical life expectancy curves for 175W, 400W, and 1000W jacketed mercury lamps at various burning cycles.

Unjacketed mercury HID lamps have life in the range of 500 to 1000 hours. When operated at rated wattage in 8-hour buring cycles, 500 and 800W lamps should have life exceeding 500 hours with maintenance of at least 80% of initial lumen output. Life can be extended by switching to half-power during standby periods.

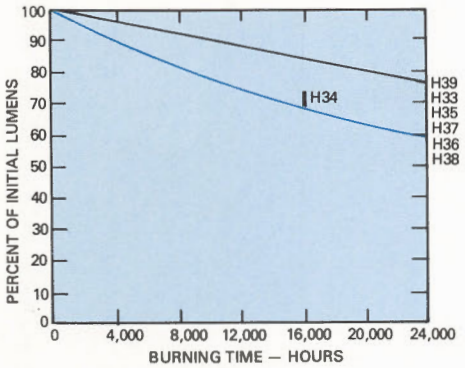


Figure 4.1-10 Approximate lumen maintenance of typical clear mercury lamps operating horizontally.

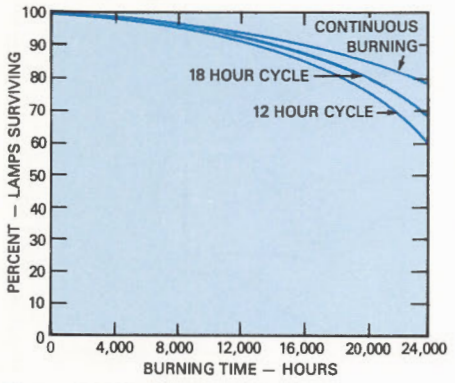


Figure 4.1-11 Life expectancy curves for 175W, 400W, 1000W jacketed mercury HID lamps.

4.2 Metal-Halide Lamps

Metal-halide HID lamps are among the most efficient sources of white light having significantly higher efficacy than mercury HID lamps, good lumen maintenance, economically reasonable life, and excellent color rendition. They are available from Sylvania in various jacketed and unjacketed configurations. The jacketed configurations, designated Metalarc lamps and Super Metalarc lamps, are used mainly for lighting. The unjacketed configurations, called tubular metal-halide HID lamps, are used mainly in reprographic and photochemical applications, but one particular tubular metal-halide HID lamp designated the Brite-Line lamp is designed for lighting.

Principles of Operation

Metal-halide lamps operate in electrical circuits similar to the mercury lamp circuit of Figure 4.1-1, but usually require special ballasts because the presence of metal halides in the arc tubes increases the starting voltage requirements and causes significant differences in operating characteristics.

The Halogen Cycle

The arc tubes in both metal-halide and mercury HID lamps contain mercury and an inert starting gas, but metal-halide arc tubes also contain additives in the form of various metal halides (e.g., scandium iodide, sodium iodide, and thorium iodide). These halides condense on the arc-tube walls when the lamp is cold, but during operation the arc discharge heats the arc-tube walls and some of the metal halides evaporate from the walls to enter the halogen cycle. The quantities of the metal halides in the vapor state depend on the temperature of the coldest spot on the arc tube wall.

The temperature gradient from the high-temperature core of the arc to the colder walls of the arc tube causes continuous circulation of the gases and vapors within the arc tube. As the halide vapor moves in toward the high-temperature region its temperature rises to that at which it dissociates into free metal and halogen molecules, and the hot metal atoms then contribute their characteristic line spectra to that of the mercury discharge. The general circulation then carries the metal and halogen molecules out towards the cooler walls, and the temperature of the molecules falls to that at which they recombine to form halogen vapor. In order for this halogen cycle of dissociation, excitation, and recombination to contribute significant radiation to the spectral output of the lamp, the arc-tube walls must be maintained at a sufficiently high temperature to provide a significant vapor pressure of metal halide at the walls.

The halogen cycle permits use of metals having desired spectral characteristics in cases where the pure metallic forms are unsuitable. For example: the pure metal may not evaporate at temperatures within the operating range of the arc tube, while the halide of that metal evaporates at safe operating temperatures; or the pure metal (e.g., sodium) may be highly reactive with fused quartz but the halide of that metal is not reactive. In the latter example, note that only the non-reactive halide exists at the walls of the arc tube, and that the reactive pure metal exists only at the hot center of the arc discharge.

Types of Metal-Halide Lamps

Metalarc lamps are jacketed metal-halide HID lamps with cylindrical arc tubes. They are available with clear or phosphor-coated jackets, in ratings from 175W to 1500W, for base-up to horizontal operation, for base-up operation, and for base-down operation. Metalarc lamps have about 65% to 70% greater efficacy than jacketed mercury HID lamps of equal wattage.

Super Metalarc lamps are jacketed metal-halide HID lamps with specially-shaped arc tubes. They are available with clear and phosphor-coated jackets, in ratings from 175W to 1000W, for horizontal operation, for base-up vertical operation, and for base-down vertical operation. They have almost 100% greater efficacy than jacketed mercury HID lamps of equal wattage, and about 25% greater efficacy than standard Metalarc lamps of equal wattage.

Tubular metal-halide HID lamps are unjacketed lamps for reprographic and photochemical applications. They are made of clear fused quartz, in ratings from 400W to 4000W, for horizontal operation only.

Brite-Line lamps are unjacketed 1500W tubular metal-halide HID lamps intended for horizontal operation in general illumination applications.

Physical Characteristics

Construction of Metalarc Lamps

Metalarc lamps are similar in external appearance to jacketed mercury HID lamps but the construction and mounting of the arc tubes are different, as shown in Figure 4.2-1. This represents a base-up Metalarc lamp. In base-down lamps the arc tube is inverted in the jacket so that the starting electrode and bimetal shorting switching are at the dome end of the bulb.

The fused-quartz arc tube of the Metalarc lamp is slightly smaller than that of a jacketed mercury HID lamp of the same wattage. The arc tube contains argon gas, mercury, and the iodides of sodium and scandium. These last two are the metal halides for which this type of lamp is named. During operation the arc tube is heated by the discharge and the iodides evaporate at a rate determined by the temperature of the coldest portion of the arc tube, where excess iodides condense out. To reduce heat losses through leads and supports which would otherwise cause the ends to be the coolest parts of the arc tube and to maintain the ends of the arc tube at suitably high operating temperatures, heat-retentive coatings are applied to the ends.

The arc-tube support system employs split-frame construction in which a separate harness is fastened to each end of the arc tube. The arc-tube harness assembly is supported within the jacket by means of springs at the neck and at the dome. This split-frame construction is necessitated by the high electrochemical activity of the metal halides which requires maximum possible isolation of the arc tube.

Electrodes are sealed into the ends of the arc tube as in jacketed mercury HID lamps and are connected as shown in Figure 4.1-1. The operating electrodes are thoriated-tungsten coils.

A bimetal shorting switch is mounted across the rigid leads of the starting electrode and the adjacent operating electrode near where those leads enter the arc tube. The switch is open when the lamp is cold, but when the lamp warms up, the switch closes and bypasses any current that might otherwise flow through any iodide deposits on the arc-tube wall between the electrodes. This prevents electrolytic failure of the molybdenum foils in the end seals of those electrodes. The 1000W and 1500W Metalarc lamps use a solid-state diode in addition, to augment the action of the bimetal shorting switch during lamp warmup.

Jacket bulbs identical to those of jacketed mercury HID lamps of equal wattage protect the arc tubes from atmospheric corrosion and regulate the arc-tube operating temperature. The jackets are made of borosilicate hard glass to absorb ultraviolet radiation emitted by the arc tube and are usually filled with an inert gas such as nitrogen.

Mogul screw bases are used on all Metalarc and Super Metalarc lamps.

Phosphor coating is available for use where even better color rendition is required than that from clear Metalarc lamps. Phosphor-coated Metalarc lamps are designated Metalarc/C lamps.

Construction of Super Metalarc Lamps

These lamps are made with specially-shaped arc tubes to assure optimium performance of the halogen cycle in the operating positions for which the lamps are designed.

Horizontal Super Metalarc lamps. Arc discharges are so called because they tend to bow upwards between horizontal electrodes to form a geometric arc. In horizontal metal-halide lamps with straight cylindrical arc tubes, the upward bowing of the arc heats the upper part of the arc tube more than the lower part, on which metal halides therefore condense. This reduces the halide content of the discharge which adversely affects both efficacy and color. As shown in Figure 4.2-2, horizontal Super Metalarc lamps employ arc tubes that arch upward between the ends to accomodate the natural upward bowing that occurs in horizontal arcs. Since the axis of the tube is aligned with the high-temperature core of the arc, the arc-tube walls are heated evenly. This increases the amount and uniformity of the metal halides in the discharge, resulting in more uniform color and in approximately 25% higher efficacy than for comparable Metalarc lamps with straight cylindrical arc tubes. Horizontal Super Metalarc lamps are presently made in 175W and 400W ratings, and have the same ballasting requirements as standard Metalarc lamps of equal wattage.

Since the horizontal Super Metalarc lamp must be positioned so that the arc tube bends upward, it is made with a position-oriented mogul base (POMB) which fits a position-oriented mogul socket (POMS). The POMB shell has a locating pin that positively stops the lamp in a cutout in the POMS which must be installed in the lamp fixture so that the longitudinal axis of the lamp is within 15° of the horizontal plane and the vertical centerline of the arc tube is within 15° of the vertical.

Vertical Super Metalarc lamps. Arc discharges in vertically-operated cylindrical metal-halide arc tubes tend to separate into upper and lower convection patterns containing differing amounts of metal halides. The lower pattern contains more of the halides and thus has the typical output of a metal-halide lamp, while the upper pattern contains less of the halides and thus has an output which is closer to that of a mercury HID lamp. The total lamp output is the average of the outputs of the two patterns. As

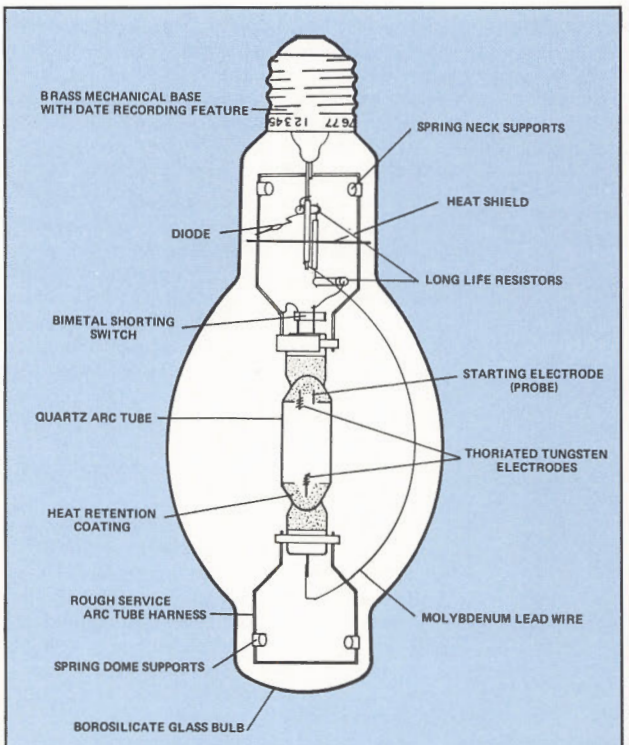


Figure 4.2-1 Construction of a 400W base-up Metalarc lamp.

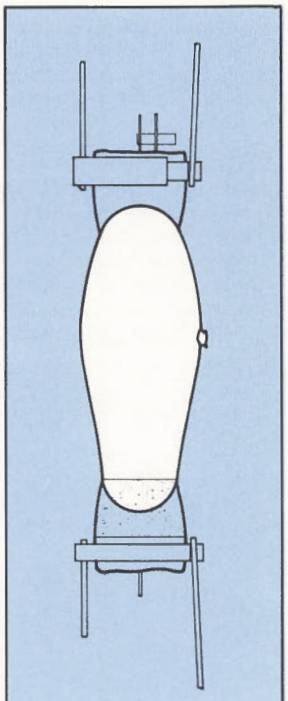


Figure 4.2-3 Arc tube of the MS1000 vertical Super Metalarc lamp.

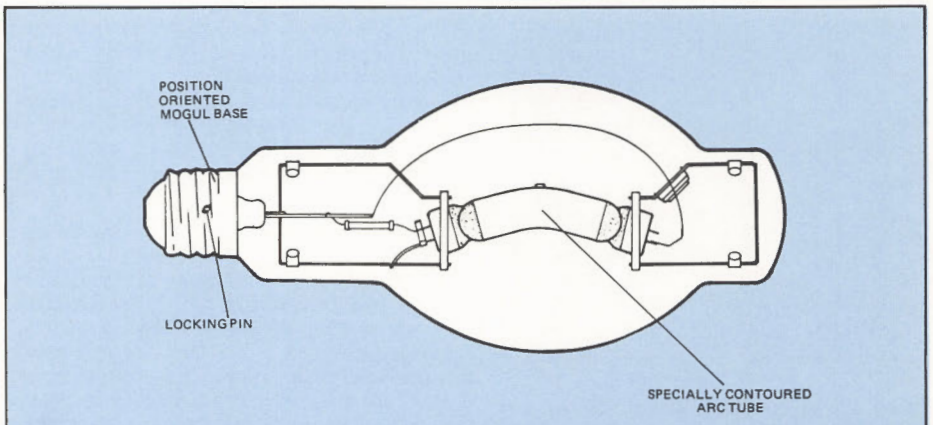


Figure 4.2-2 Construction of horizontal Super Metalarc lamps. The major differences from standard Metalarc lamps are labeled.

shown in Figure 4.2-3, vertical Super Metalarc lamps have arc tubes with expanded sections; these cause the convection currents to flow in a single pattern which increases the halide content of the arc and thus increases the efficacy about 25% over vertical Metalarc lamps with straight cylindrical arc tubes.

Vertical Super Metalarc lamps are presently made only in 400W and 1000W ratings for base-up operation or for base-down operation, and have the same ballasting requirements as standard 1000W Metalarc lamps.

Construction of Unjacketed Metal-Halide Lamps

Tubular metal-halide lamps for reprographic and photochemical applications are made of clear fused quartz in the five base configuration shown in Figure 4.1-4, and with the same ranges of physical parameters as the unjacketed tubular mercury HID lamps discussed in Section 4.1. Electrical parameters are also similar, except that tubular metal-halide lamps require the same types of special ballasts as Metalarc lamps. The same precautions must be taken as for tubular mercury HID lamps to prevent exposure of personnel to erythemal ultraviolet radiation emitted from the arc tube.

Brite-Line lamps are 1500W tubular metal-halide HID lamps made of clear fused quartz, in T7 bulbs with 7-inch lighted length and 10-1/16 inch maximum overall length, and are designated MW1500T7/7H. They have single-contact bases (see Figure 4.1-4a) identical to those commonly used on tubular tungsten-halogen lamps for which sockets are readily available. They must be used only in luminaires with ultraviolet-absorbing faceplates to prevent transmission of hazardous erythemal radiation emitted from the arc tube.

Illumination Characteristics

Lumen Output and Efficacy

The lumen outputs and efficacies of metal-halide HID lamps are much greater than those of equal-wattage mercury HID lamps. For example, the lumen outputs and efficacies of Metalarc lamps are about 65% to 70% greater, and those of Super Metalarc lamps are about 100% greater, than those of equal-wattage mercury HID lamps.

Spectral Power Distribution and Color Temperature

SPD curves of various jacketed metal-halide HID lamps are given in Figures 4.2-4 through 4.2-7. The SPD curves for clear and phosphor-coated 400W Metalarc lamps are given in Figures 4.2-4 and 4.2-5. These differ slightly from those of Metalarc lamps of other wattages. The SPD curves for clear and phosphor-coated horizontal 400W Super Metalarc lamps are given in Figures 4.2-6 and 4.2-7, for comparison with those of the standard Metalarc lamps. These differ slightly from the SPD curves for Super Metalarc lamps of other wattages and operating positions.

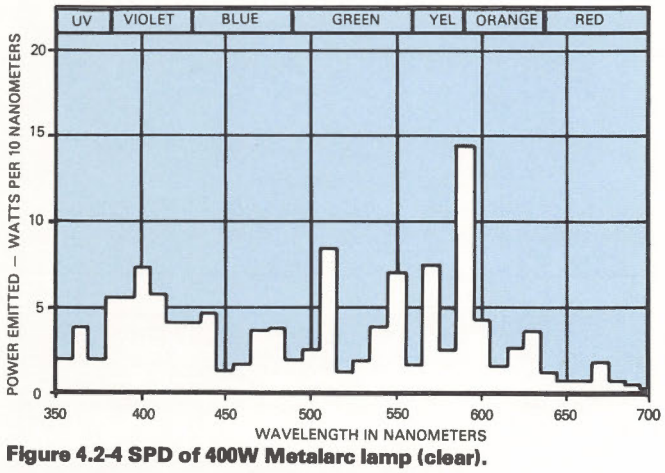


Figure 4.2-4 SPD of 400W Metalarc lamp (clear).

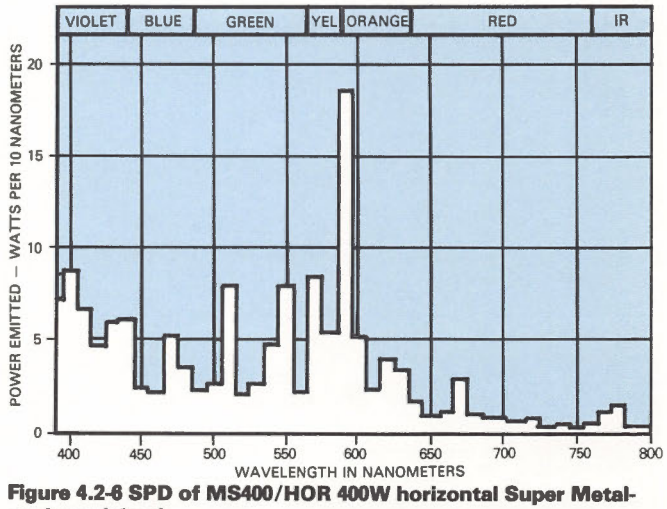


Figure 4.2-6 SPD of MS400/HOR 400W horizontal Super Metalarc lamp (clear).

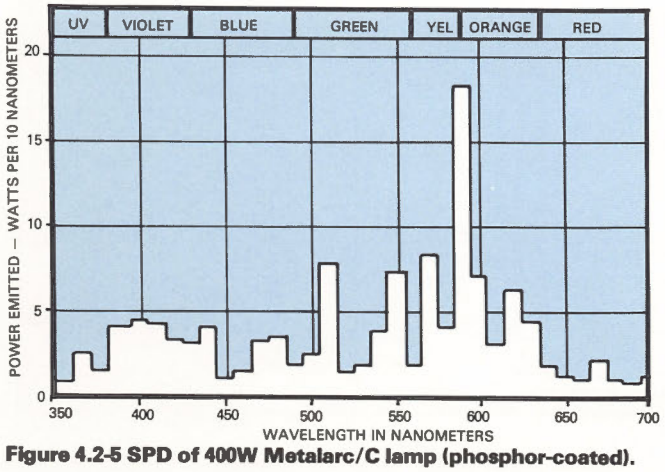


Figure 4.2-5 SPD of 400W Metalarc/C lamp (phosphor-coated).

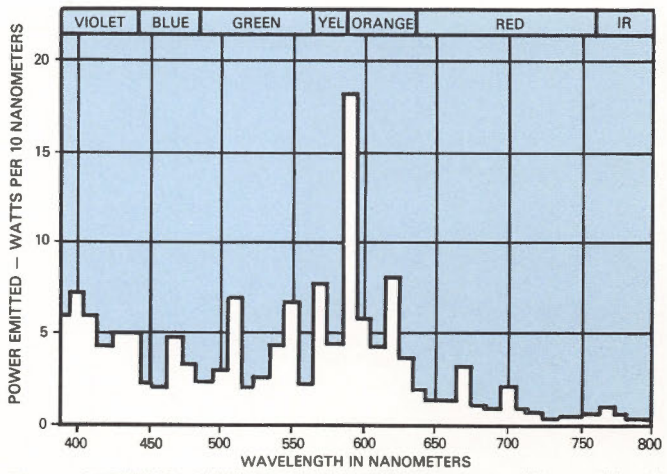


Figure 4.2-7 SPD of MS400/C/HOR 400W horizontal Super Metalarc/C lamp (phosphor-coated).

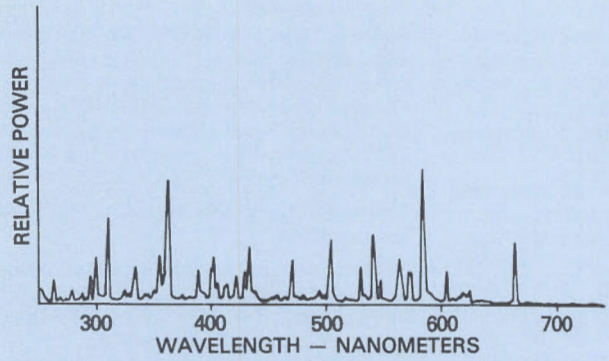


Figure 4.2-8 SPD of 1500W Brite-Line lamp.

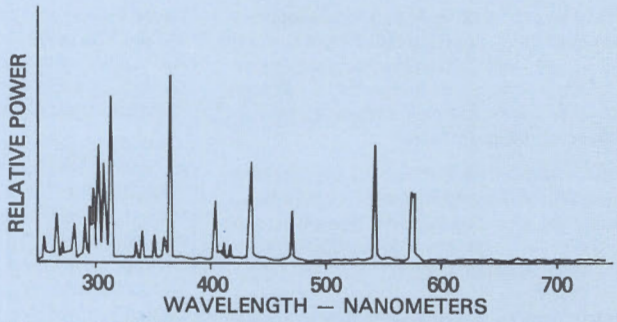


Figure 4.2-9 SPD of typical ultraviolet tubular metal-halide lamp.

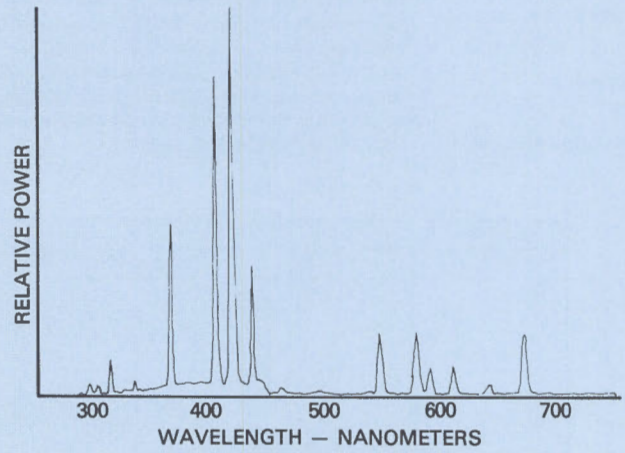


Figure 4.2-10 SPD of typical MP-series diazo (purple) tubular metal-halide lamp.

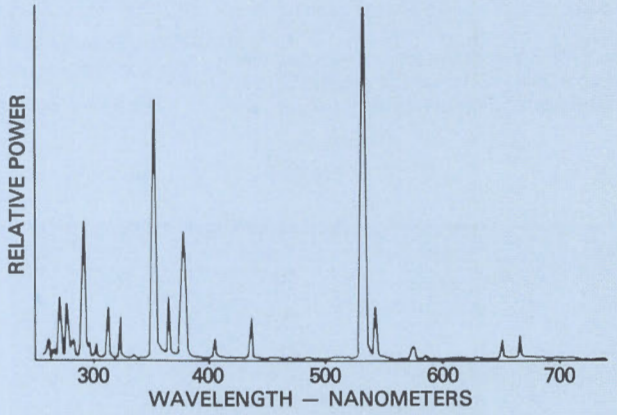


Figure 4.2-11 SPD of typical MG-series (green) tubular metal-halide lamp.

LAMP TYPE	INITIAL LUMENS (vertical)	LAMP EFFICACY (LM/W)	CIE CHROMATICITY X	CIE CHROMATICITY Y	CORRELATED COLOR TEMP. APPROXIMATE	CIE COLOR-RENDERING INDEX
METALARC (CLEAR)						
175W	14,000	80	.356	.382	4,700K	65
400W	34,000	85	.362	.371	4,500K	65
1000W	100,000	100	.382	.372	4,000K	65
METALARC/C (PHOSPHOR—COATED)						
175W	14,000	80	.403	.388	3,600K	70
400W	34,000	85	.390	.388	3,800K	70
1000W	100,000	100	.400	.375	3,400K	70
SUPER METALARC (CLEAR)						
175W	15,000	86	.353	.382	4,700K	65
400W	40,000	100	.360	.365	4,500K	65
1000W	125,000	125	.400	.375	3,500K	65
SUPER METALARC/C (PHOSPHOR—COATED)						
175W	15,000	86	.373	.380	3,900K	70
400W	40,000	100	.385	.368	3,800K	70
BRITE—LINE 1500W	150,000 (horizontal)	100	.383	.366	3,800K	

Figure 4.2-12 Initial lumens, lm/W, and color characteristics of typical metal-halide lamps.

SPD curves of various tubular metal-halide lamps are given in Figures 4.2-8 through 4.2-11. Figure 4.2-8 gives the SPD curve of the 1500W Brite-Line lamp, and Figures 4.2-9 through 4.2-11 give the SPD curves of various tubular metal-halide lamps for reprographic and photochemical applications.

Correlated color temperature, CIE chromaticity, and CIE color-rendering index of typical metal-halide lamps are listed in Figure 4.2-12.

Operating Characteristics

Auxiliary Components and Circuits

Special ballasts are required for satisfactory starting, warmup, and operation of most metal-halide lamps. The ballasts must not only supply higher starting voltages than for mercury HID lamps but must match the varying electrical characteristics of the lamp during warmup. Figure 4.2-13 shows the warmup characteristics of a 400W Metalarc lamp. To provide good lumen maintenance over lamp life, lead-peak ballasts are used to supply a peaked open-circuit voltage waveform with a crest factor (i.e., ratio of peak to rms value) of about 1.8. Ballasts supplying sinewave open-circuit voltages having the same peak values are also satisfactory but are larger and more expensive.

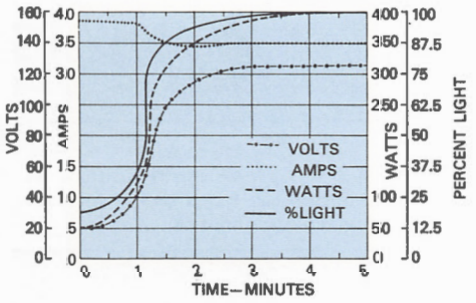


Figure 4.2-13 Warmup characteristics of a 400W Metalarc lamp.

Some types of mercury lamp ballasts can provide minimally-adequate electrical parameters to metalarc lamps during warm up. For operation on such ballasts, specially-designed lamps, designated as Metalarc Swingline, incorporating an internal voltage doubler circuit for increasing the starting voltage applied to the arc tube, can yield acceptable life performance as replacements for mercury lamps in existing installations. However, lumen maintenance and life are both poorer than for Metalarc lamps operated on metal-halide-rated ballasts, and the use of mercury lamp ballasts for new installations of Metalarc lamps is not recommended.

Effects of line-voltage variation on lamp wattage are shown in Figure 4.2-14 for metal-halide lamps operated with lead-peak ballasts and with reactor ballasts. Note that the per cent change in lamp watts with line voltage variation is greater with reactor ballasts than with lead-peak ballasts. If the average line voltage at the ballast is not the nominal line voltage, and if the ballast has taps for operation at other than nominal voltage, best lamp performance will be achieved by using the tap most closely matching the average line voltage.

Effects of operating position. Metalarc lamps are made in versions for operation in specific positions such as base-up (BU) or base-down (BD), or over a range of positions such as base-up to horizontal (BU-HOR); although not all wattage ratings are made in all three versions. Most BU and some BD lamps are restricted to operation within 15° of vertical, but some BD lamps may be operated from base-down up to but not including the horizontal. Super Metalarc lamps are made in HOR, BU, and BD versions, and must be operated within 15° of their specified positions. Tubular metal-halide lamps generally must be operated with 4° of horizontal.

Published ratings are established for lamps operating in specified positions, and operation in other positions will cause deviations from those ratings. For example, operation of BU or BD Metalarc lamps in positions other than vertical causes slight reduction in lamp wattage, lumen output, lumen maintenance, and mean lumens over life. The operating positions causing the lowest lumen output (and which should therefore be avoided) are approximately 20° to 30° from horizontal (60° to 70° from vertical).

Effects of temperature. Starting of cold metal-halide lamps, whether jacketed or unjacketed, is more difficult at low ambient temperatures which reduce the mercury vapor pressure and necessitate higher starting voltages. After warmup, the operation of jacketed lamps is essentially independent of ambient temperature because the outer jacket controls the arc tube operating temperature. Wattage, lumen output, and color therefore do not vary appreciably with ambient temperature. However, ambient temperature can affect ballast performance which in turn can affect lamp operation. While the arc tube is protected and relatively independent of ambient lamp environmental temperature, refocusing or concentration of energy or use of auxiliary equipment such that internal lamp components are subjected to abnormal thermal, mechanical, or electrical conditions must be avoided.

Jacket temperatures must be limited to 400°C maximum, and base temperature must be limited to 210°C maximum.

Brite-Line and other unjacketed tubular metal-halide lamps do not have the thermal insulation afforded by outer jackets and are thus sensitive to ambient temperature variation even during operation. They therefore must be enclosed in luminaires which will maintain optimum bulb operating temperatures while not overheating the seals. The bulb temperatures must be limited to 800°C maximum, and the seal temperatures must be limited to 500°C maximum.

Warmup and restrike times. The warmup time from a cold start to 80% of maximum output is 2 minutes for all Super Metalarc lamps and for all Metalarc lamps except the 1000W and 1500W for which the warmup times are 4 minutes and 5 minutes respectively. The warmup time for tubular metal-halide lamps like the Brite-Line is about 6 minutes.

Metal-halide lamps cannot be started again immediately after a power interruption because the pressure in the hot arc tube is too great for the ballast voltage to be able to ignite the discharge. When the arc tube has cooled so that the pressure in it is low enough, the ballast can again ignite the discharge. Since the arc tube is well insulated by the jacket, this cooling takes considerable time. Hot restart or restrike times are 10 minutes for all Super Metalarc lamps and for all Metalarc lamps except the 1500W, for which the restrike time is 15 minutes.

Lumen maintenance of metal-halide lamps varies with wattage, with operating hours per start, and with operating position. Lumen maintenance to end of life is about 5% lower for horizontal operation than for vertical operation. Lumen maintenance is generally lower for phosphor-coated than for clear lamps, as illustrated in Figures 4.2-15 through 4.2-17 which are curves for vertically-operated 400W Metalarc and Super Metalarc clear and phosphorcoated lamps at various burning cycles.

Since mercury ballasts generally provide a more peaked current waveform with a higher current crest factor than metal-halide ballasts as well as a tendency to start the lamp with a larger period of glow discharge before establishing the full arc, the Metalarc Swingline has slightly shorter rated life and lower lumen maintenance than other 400W Metalarc lamps operating with metal-halide ballasts, and is therefore recommended for use only as a replacement for 400W mercury HID lamps in existing installations.

The lumen maintenance of 1500W Brite-Line lamps at 4 hours per start is shown in Figure 4.2-18; longer burning cycles will give better lumen maintenance.

Lamp life is a function of operating hours per start, with longer burning cycles yielding longer life. Figures 4.2-19 through 4.2-21 show life expectancy curves of 400W Metalarc lamps, 400W Super Metalarc lamps, and 1500W Brite-Line lamps at various burning cycles.

Life of tubular metal-halide lamps can be extended greatly by using rated loadings during actual use and switching to half-rated loadings during standby. Note that unless half-power switching is specified when ordering these lamps, they will not be tested and guaranteed for switching reliability.

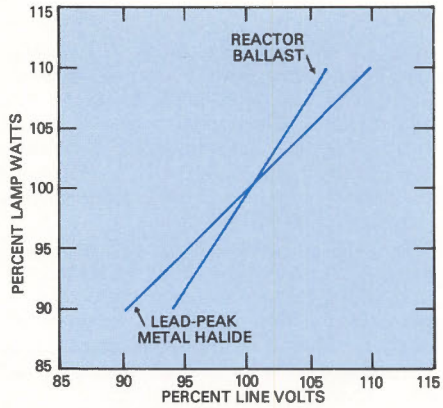


Figure 4.2-14 Effect of line voltage variation on metal-halide lamp wattage.

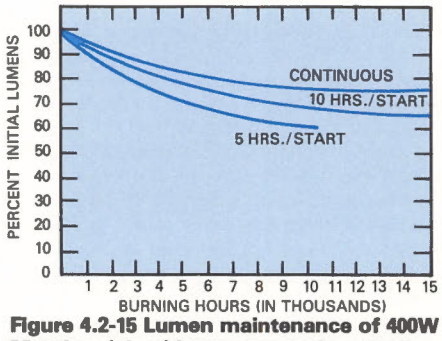

CONTINUOUS
10 HRS./START
5 HRS./START
PERCENT INITIAL LUMENS
BURNING HOURS (IN THOUSANDS)
100 90 80 70 60 50 40 30 20 10 0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15

Figure 4.2-15 Lumen maintenance of 400W Metalarc (clear) lamp operated vertically.

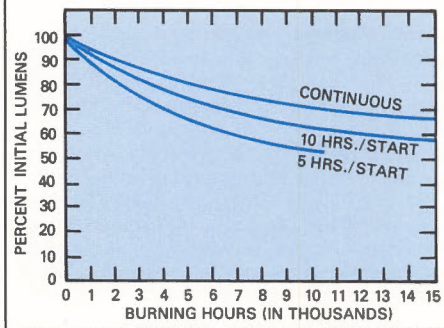

CONTINUOUS
10 HRS./START
5 HRS./START
PERCENT INITIAL LUMENS
BURNING HOURS (IN THOUSANDS)
100 90 80 70 60 50 40 30 20 10 0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15

Figure 4.2-16 Lumen maintenance of 400W Metalarc/C (phosphor-coated) lamp operated vertically.

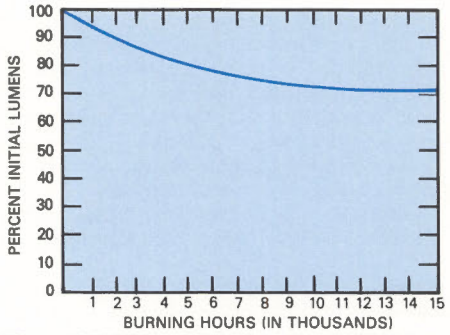


Figure 4.2-17 Lumen maintenance of 400W Super Metalarc (clear) and 400W Super Metalarc/C (phosphor-coated) lamp on ten-hour burning cycle.

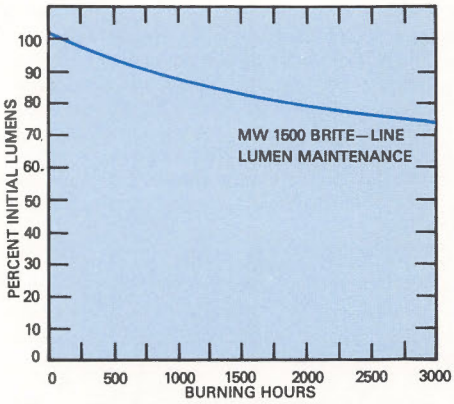

MW 1500 BRITE—LINE
LUMEN MAINTENANCE
PERCENT INITIAL LUMENS
BURNING HOURS
100 90 80 70 60 50 40 30 20 10 0
0 500 1000 1500 2000 2500 3000

Figure 4.2-18 Lumen maintenance of MW1500 Brite-Line lamp based on four hours of operation per start.

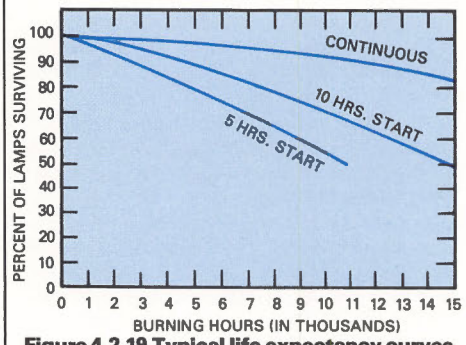

CONTINUOUS
10 HRS. START
5 HRS. START
PERCENT OF LAMPS SURVIVING
BURNING HOURS (IN THOUSANDS)
100 90 80 70 60 50 40 30 20 10 0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15

Figure 4.2-19 Typical life expectancy curves for 400W Metalarc lamps at various burning cycles, when operated on single-lamp ballast or independently on (parallel) dual ballast).

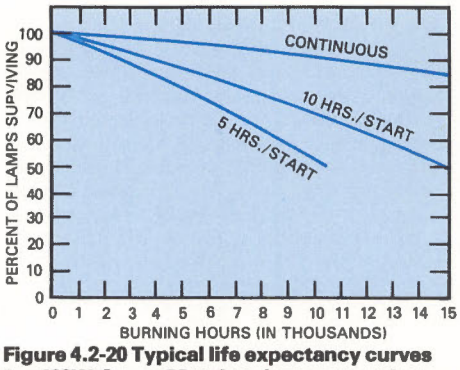

CONTINUOUS
10 HRS./START
5 HRS./START
PERCENT OF LAMPS SURVIVING
BURNING HOURS (IN THOUSANDS)
100 90 80 70 60 50 40 30 20 10 0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15

Figure 4.2-20 Typical life expectancy curves for 400W Super Metalarc lamps at various burning cycles, when operated on single-lamp ballast or independently on (parallel) dual ballast.

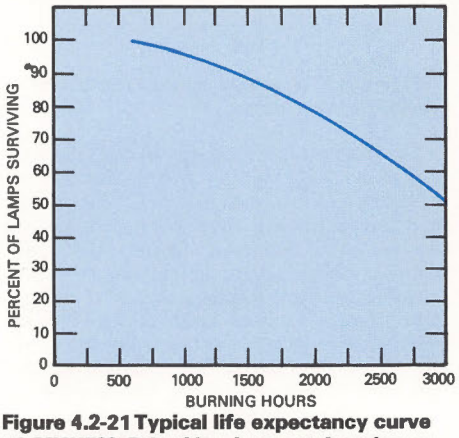


Figure 4.2-21 Typical life expectancy curve of MW1500 Brite-Line lamp at four hours per start.

4.3 Medium Pressure Sodium (HID) Lamps

Medium-pressure sodium lamps have the highest efficacies (80 to 140 lm/W) of all HID lamps, as well as fair color rendition, high lumen maintenance, and long life. These lamps, which operate at the low end of the medium-pressure range (200 torr, or about 0.27 atm), are also called **high-pressure sodium (HPS)** lamps because they operate at about 40,000 times the pressure (0.005 torr, or 6.6×10^{-6} atm) of the low-pressure sodium lamps described in Section 3.2. HPS lamps are available from Sylvania in two jacketed versions called Lumalux and Unalux lamps, typical characteristics of which are listed in Figure 4.3-1.

Lumalux lamps, which require special ballasts, are available in ratings from 70W to 1000W.

Unalux lamps are designed to operate on certain types of mercury HID lamp ballasts and to be physical and electrical replacements for mercury HID lamps of comparable wattages. They are available in 150W, 215W and 360W ratings.

LAMP DESIGNATION	BULB	INITIAL EFFICACY LM/W	FIXTURE EFFECT VOLTAGE RISE LIMIT
LU 50/Med	A-23	66	4
LU 100	BT-25	95	4
LU 250	E-18	110	10
LU 400	E-18	125	14
LU 1000	E-25	140	25
ULX 150	BT-28	80	10
ULX 360	BT-37	100	10

Figure 4.3-1 Reference data for typical Lumalux and Unalux lamps.

Lumalux Lamps

Physical Characteristics of Lumalux Lamps

HPS lamps, like other jacketed HID lamps, have inner bulbs or arc tubes enclosed within outer bulbs or jackets. HPS lamps generate light by means of an electrical discharge through hot sodium vapor, which will react with and destroy fused-silica arc tubes. The arc tubes in HPS lamps therefore differ from those of all other HID lamps in that they are not made of fused silica but of polycrystalline alumina which is highly resistant to attack by hot sodium vapor.

Construction of Lumalux lamps (Figure 4.3-2) is generally similar to that of other HPS lamps, but employs monolithic construction of the arc tube (Figure 4.3-3).

The arc tube in Lumalux lamps is made of alumina (polycrystalline aluminum oxide), a ceramic material which has extreme resistance to attack by hot sodium vapor, a high melting point, and (although it is translucent but not transparent) over 90% transmittance in the visible. As Figure 4.3-3 shows, the arc tube is monolithic because it is sealed at each end with a ceramic button of material identical to that of the tube itself. A niobium tube through each end button supports an electrode within the arc tube. Each niobium tube is sealed around the electrode to maintain the arc tube pressure, but the outer ends of the niobium tubes are left open. This permits the arc tube to be supported

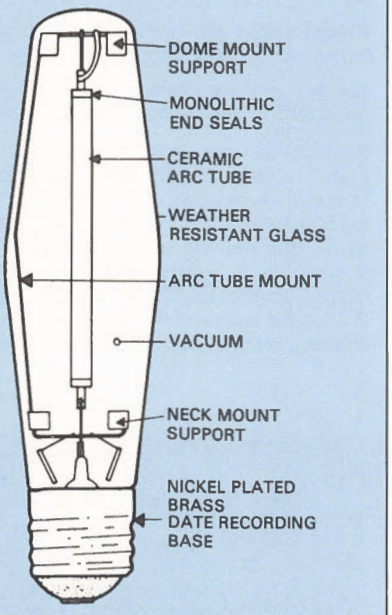


Figure 4.3-2 Construction of Lumalux lamps.

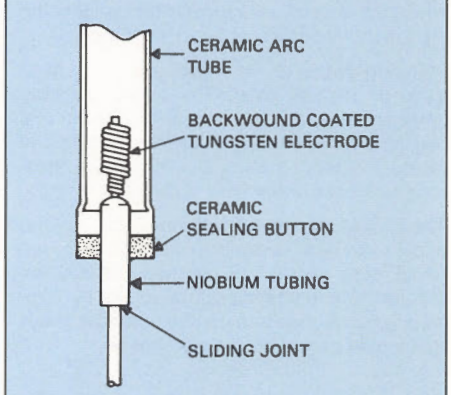


Figure 4.3-3 Construction of monolithic arc tube.

and aligned within the jacket by centering rods which project into the open ends of the niobium tubes. The niobium tubes can slide on the centering rods; these sliding joints permit axial thermal expansion while preventing transverse displacement of the arc tube.

The arc-tube fill consists of a sodium-mercury amalgam and xenon gas at low pressure. The xenon is a starting gas which reduces the voltage required to strike the arc. As the arc tube heats up to operating temperature, the mercury and sodium partially vaporize. The mercury vapor acts as a buffer gas which raises the pressure inside the arc tube, and the voltage across the arc tube, to the operating values at which the hot sodium vapor produces light having the desired spectral power distribution.

During operation, the ends are the coldest parts of the arc tube. The sodium-mercury amalgan forms at whichever end is coolest and acts as a reservoir which supplies sodium and mercury vapor to the arc. The lamps may therefore be burned either base up or base down.

The jacket is made of lead borosilicate glass, and is evacuated to prevent oxidation of the external metal parts of the arc tube and to maintain arc tube operating temperatures by eliminating convection and conduction heat losses that would occur with an inert gas fill.

A spectrally-neutral diffusing coating may be applied to the inner surface of the jacket to provide larger effective source size and lower luminance than that of the arc tube itself. This coating does not affect lamp color, but reduces lumen output and efficacy by 5% to 7%.

Mogul screw bases are used on all Lumalux lamps.

Illumination Characteristics of Lumalux Lamps

Initial lumens and efficacy range from 5800 lm and 83 lm/W for the 70W clear lamp to 140,000 lm and 140 lm/W for the 1000W clear lamp.

Mean lumens throughout life are 90% of initial lumens, on 10-hour duty cycles.

Lumens maintenance (Figure 4.3-4) is high, being 80% at the end of 24,000 hours rated life.

Spectral power distribution of a 400W Lumalux lamp (Figure 4.3-5) is typical of Lumalux lamps 70W to 1000W. The quasi-continuous spectra of HPS lamps are quite different from the line spectra of low-pressure sodium lamps (Figure 3.2-2) because at the higher pressures the 589.0 and 589.6nm sodium D lines are self-reversed and radiate as broad continua on both sides of the D wavelengths.

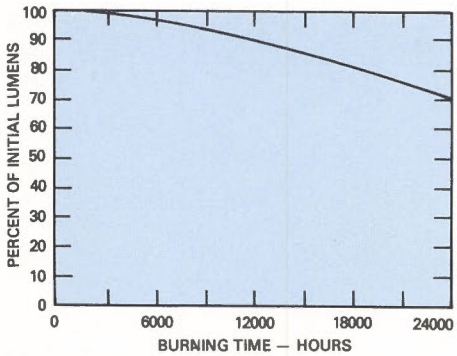


Figure 4.3-4 Lumen maintenance of typical Lumalux lamps.

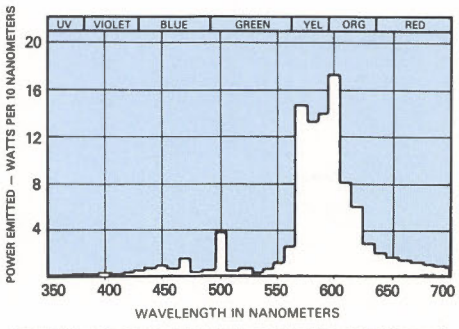


Figure 4.3-5 Spectral power distribution of 400W Lumalux lamp.

The characteristic golden-white output, while somewhat deficient in violet, blue, and green, has fair color rendition. Note that, unlike other HID lamps, Lumalux lamps have negligible output in the ultra-violet region.

The spectral power distribution shown in Figure 4.3-5 is measured after warm-up and stabilization. During the 3-4 minute warm-up period there are several changes in the brightness and color of the light: first, the dim bluish-white glow of xenon; second, the brighter blue of mercury; third, the still brighter monochromatic yellow of low-pressure sodium; and last, after build-up to operating pressure, full brightness with the typical golden-white color of high pressure sodium.

Correlated Color Temperature for all wattages is about 2100°K.

Operating Characteristics of Lumalux Lamps

The operating circuit of Lumalux lamps is shown in Figure 4.3-6. Since several electrical characteristics of these lamps (e.g., starting and operating voltages, and operating current) are considerably different from those of other HID lamps, a special ballast must be used.

The special ballast required for Lumalux lamps contains an electronic starting circuit and a magnetic component. Besides performing the usual function of striking the arc, supplying sufficient open-circuit voltage to maintain the arc, and limiting lamp current, the ballast is designed to regulate lamp power as a function of lamp voltage, as shown in Figure 4.3-7.

The power-regulating characteristic of the ballast extends life as follows. Through various processes, sodium may be lost during lamp life, reducing the amount of sodium in the sodium-mercury amalgam contained in the arc tube. This causes the sodium pressure to decrease and the mercury pressure to increase. As the ratio of sodium to mercury pressure changes, the lamp operating voltage rises. The ballast is designed to operate the lamp at relatively constant power over a wide range of operating voltages. Ultimately, of course, the lamp operating voltage may reach a value that the ballast cannot supply. The lamp then begins to 'cycle', i.e., repeatedly start, warm up to full brightness, and then extinguish. Such cycling is a common end-of-life symptom for HPS lamps. Progressive end darkening, which raises the condensed-amalgam temperature, increases both sodium and mercury pressures and also results in an increase in lamp operating voltage during life.

The ballast characteristic shown in Figure 4.3-7 has a peak at about rated voltage; the negative slope beyond the peak causes lamp wattage to decrease as lamp voltage rises above rated voltage, and slows down the rate of increase of lamp voltage during life.

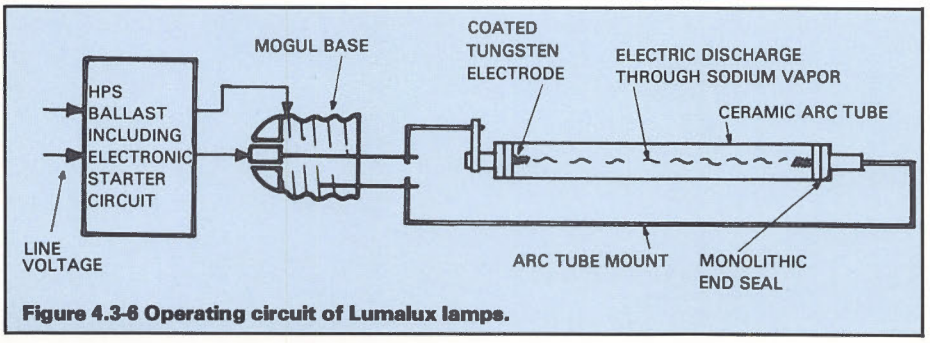


Figure 4.3-6 Operating circuit of Lumalux lamps.

The electronic starting circuit generates the high-voltage pulses required to strike the arc. These high voltages are necessitated by the arc length, the small-diameter arc tube (which precludes an internal starting electrode), and the high ionization voltage of the xenon starting gas. The electronic starting circuit operates in conjunction with the magnetic component of the ballast to generate a short high-voltage pulse on each cycle or half-cycle of the supply voltage. The pulse characteristics required by the 70 to 400W lamps are: amplitude, 2500V min, 4000V max; width, 1 sec min. The 1000W lamp requires a pulse amplitude of 3000V min, 5000V max; and width of 4 sec min.

The narrow starting pulses have high-frequency components which are attenuated rapidly over short distances. Too great a distance between the starting circuit and the lamp will reduce starting reliability. The manufacturer of each ballast specifies a maximum allowable ballast-to-lamp distance for reliable starting.

When a Lumalux lamp fails or is removed, the starting circuit operates continuously, which may have adverse effects on ballast life. Defective or removed lamps should be replaced within the time period recommended by the manufacturer of the ballast.

Warm-up time to full, stable output is 3-4 minutes from a cold start.

Hot-restart or restrike time after momentary interruption is about 1 minute minimum, using the same pulses as for initial starting.

Fixture Effect Voltage Rise is the increase in operating voltage that occurs when a lamp is operated in a fixture, or luminaire, over that which may occur when the lamp is operated in free air. This increase, which is caused by re-radiation from the fixture to the arc tube, must be limited by the design of the fixture to the values shown in Figure 4.3-1, or lamp life will be reduced.

Operating position may be either base up or base down. This simplifies ordering and stocking and reduces the number of lamps in inventory, since one type in each wattage will satisfy requirements for both BU and BD types.

Rated Life of Lumalux lamps at 10 hours per start is 20,000 to 24,000 hours, depending on wattage.

Life expectancy is shown in Figure 4.3-8.

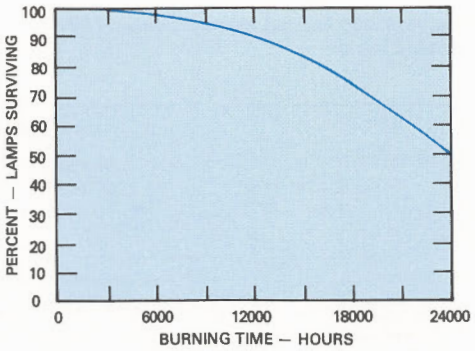


Figure 4.3-8 Life expectancy curve of typical Lumalux lamps.

Unalux Lamps

Physical Characteristics of Unalux Lamps

Construction of Unalux lamps (Figure 4.3-9) is similar to that of Lumalux lamps, and any differences result from the requirement that these lamps be retrofit replacements for mercury vapor lamps in existing installations.

The arc tube is of monolithic construction like those of Lumalux lamps and provides the same benefits; namely, reduced voltage rise over a longer life, and universal operating position. A starting-aid coiled around the arc tube is connected through a thermal circuit breaker at the base end to the electrode at the opposite end.

The arc-tube fill consists of a sodium-mercury amalgam as in Lumalux lamps, but the starting gas is a 'Penning' mixture of argon and neon which reduces the starting voltage to that supplied by most mercury lamp ballasts. The ratio of mercury to sodium in the amalgam is higher to provide the higher mercury pressure needed to achieve the same arc-voltage drop as in the corresponding mercury lamp (e.g., 130V for the 400W lamp).

The evacuated jacket is made of hard borosilicate glass with the same BT (bulged tubular) shape and the same mogul screw base as in mercury lamps. These maintain the same light center length and maximum overall length, so that Unalux lamps are physically compatible retrofit replacements for mercury lamps. All Unalux lamps are available with clear jackets; the 150W and 360W lamps are also available with the spectrally-neutral diffusing coating previously described.

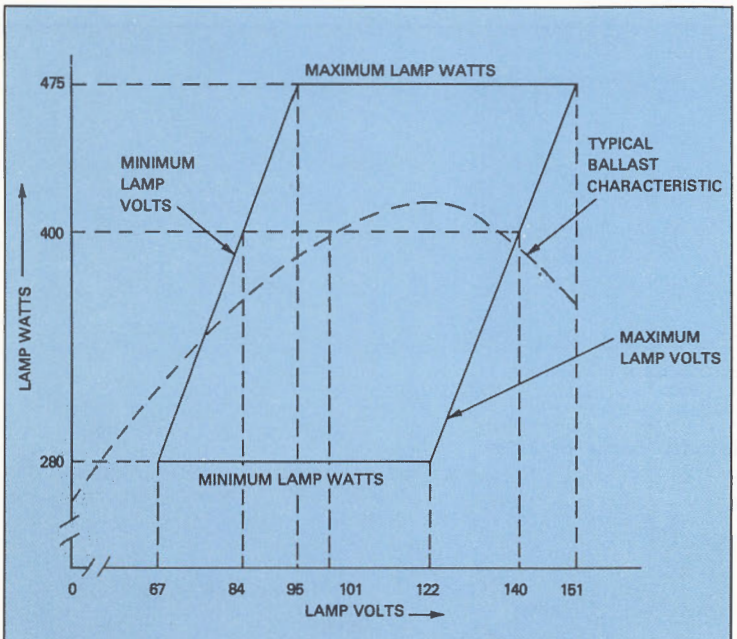


Figure 4.3-7 Lumalux ballast characteristic.

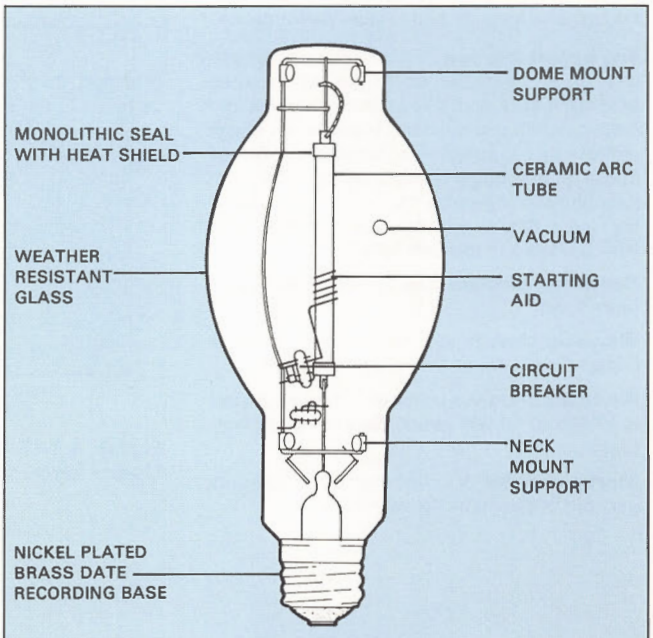


Figure 4.3-9 Construction of Unalux lamps.

Illumination Characteristics of Unalux Lamps

Initial lumens and efficacy range from 13,000 lm and 87 lm/W for the 150W clear lamps to 38,000 lm and 106 lm/W for the 360W clear lamp. Unalux lamps thus have about twice the efficacy of the mercury lamps they replace, and use 10% to 15% less power than those lamps.

Mean lumens throughout life are 90% of initial lumens, on 10-hour duty cycles.

Lumen maintenance (Figure 4.3-10) is 80% at the end of 16,000 hour rated life.

Spectral power distribution of a 360W Unalux lamp (Figure 4.3-11) is typical of all wattage ratings, and is generally similar to that of Lumalux lamps.

Correlated Color Temperature for all wattages is about 2100°K.

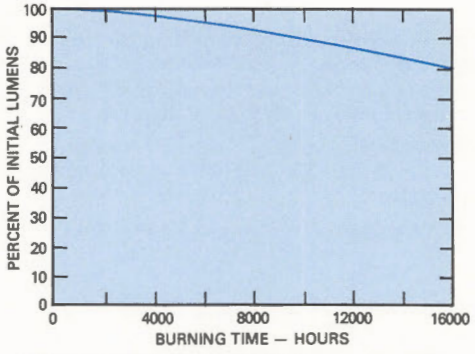


Figure 4.3-10 Lumen maintenance of 360W Unalux lamp.

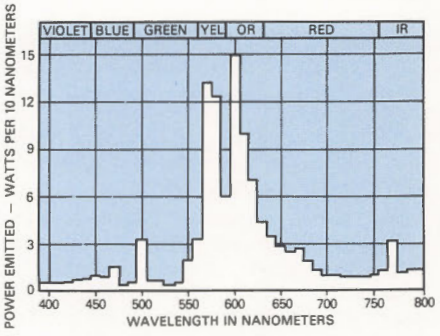


Figure 4.3-11 Spectral power distribution of 360W Unalux lamp.

Operating Characteristics of Unalux Lamps

The operating circuit of Unalux lamps is shown in Figure 4.3-12. The starting aid coiled around the arc tube is connected through a thermal circuit breaker to the electrode at the opposite end of the tube. When starting voltage is applied, ionization takes place between the starting aid and the adjacent electrode, causing the gas to become sufficiently conductive to strike the arc across the electrodes. As the lamp warms up to operating temperature, the circuit breaker opens and disconnects the starting aid. This eliminates the possibility of electrolytic processes which would accelerate sodium loss, and assures long life and reliable performance.

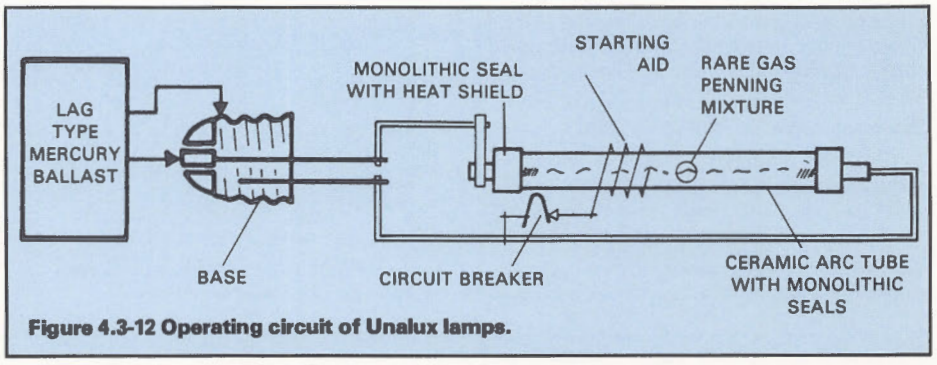


Figure 4.3-12 Operating circuit of Unalux lamps.

The ballast may be a 240V or 277V reactor ballast, an autotransformer lag ballast, or other typical mercury lamp ballast having the required wattage-voltage regulation characteristic which reduces lamp wattage as lamp voltage increases above rated voltage. Since Unalux lamps do not have the starting-pulse requirements of Lumalux lamps, they may be operated remotely from their ballasts like mercury lamps.

Operating position may be either base up or base down.

Warm-up time is about 4 minutes, and hot restart time is about 3 minutes.

Rated life of Unalux lamps at 10 hours per start is 12,000 to 16,000 hours, depending on wattage.

Mortality of 360W Unalux lamps at 10 hours per start is shown in Figure 4.3-13.

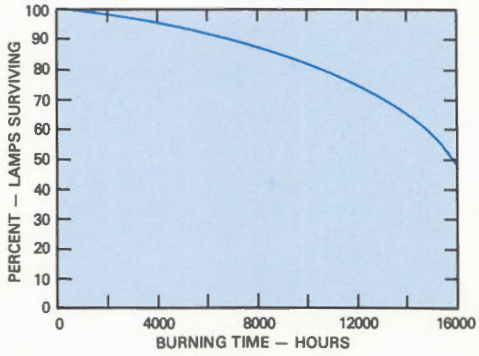


Figure 4.3-13 Mortality curve of 360W Unalux lamp.

5.0 High-Pressure Discharge Lamps

There are several major types of high-pressure discharge lamps; e.g., mercury, mercury-xenon, xenon, metal-halide, etc. Depending on type, they operate at pressures ranging from several atmospheres to more than 50 atmospheres. These lamps are also called short-arc or compact-arc lamps. Short-arc lamps have the highest luminance and radiance of all continuously operating practical light sources and are therefore used as sources in optical projection systems.

Short-arc lamps are presently available with power ratings from about 30W to about 30kW and with arc lengths ranging from less than 1mm to slightly more than 10mm.

Common characteristics of some different types of short-arc lamps are discussed in this section; characteristics unique to each type will be discussed in the following sections.

Physical Characteristics

As shown in Figure 5.0-1, short-arc lamps generally have relatively small ellipsoidal bulbs of clear fused silica, with long tubular fused-silica terminal extensions at opposite ends. Tungsten electrodes project into the bulbs from rigid support rods inside the tubular terminal extensions. Some mercury short-arc lamps have a starting electrode projecting in toward the center of the arc gap from a tubular fused-silica terminal extension at right angles to the axis of the operating electrodes. This electrode reduces the starting voltage requirements.

Except for some low-power lamps which may be operated on either ac or dc, short-arc lamps are generally designed for ac operation only or for dc operation only. In ac lamps the two electrodes are usually identical or similar but in dc lamps the positive electrode (anode) is much larger than the negative electrode (cathode), because it must dissipate more heat.

The basic double-ended short-arc lamp can be enclosed in an outer bulb or jacket, or it may be mounted integrally within a reflector.

Illuminating Characteristics

Luminance of short-arc lamps varies both along the arc and across the arc. It may vary by more than an order of magnitude or it may be relatively constant depending on the lamp type and mode of operation as shown in Figure 5.0-2. Because of these variations, the effective size of the arc depends on the optical system in which the lamp is employed as a source. The length of the arc gap is usually assumed to be the effective arc length.

Radiance is commonly assumed to be proportional to luminance, but the radiance /luminance ratio may vary significantly from point to point. This must be considered in the design of projection systems.

Flicker occurs in ac lamps at twice line frequency, but is negligible in dc lamps having adequately filtered supplies.

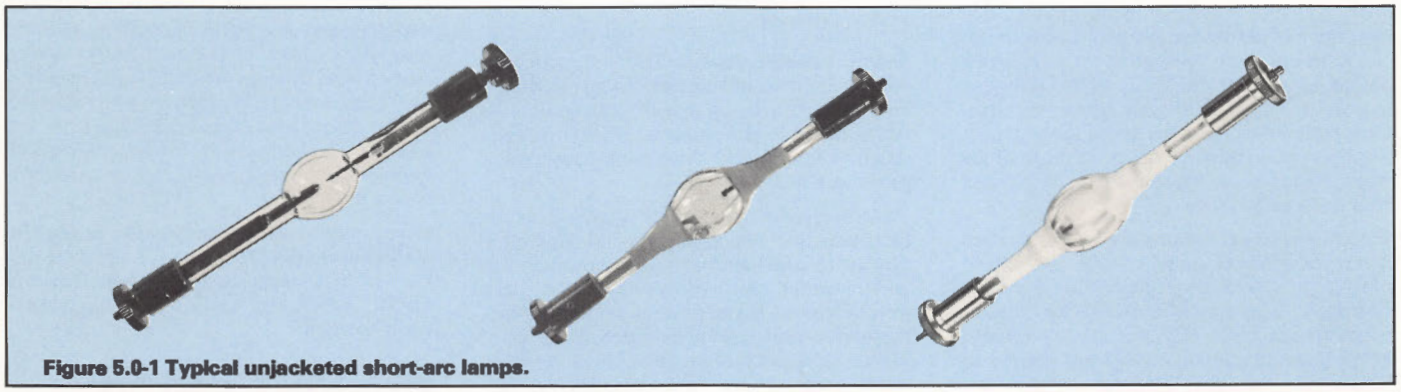


Figure 5.0-1 Typical unjacketed short-arc lamps.

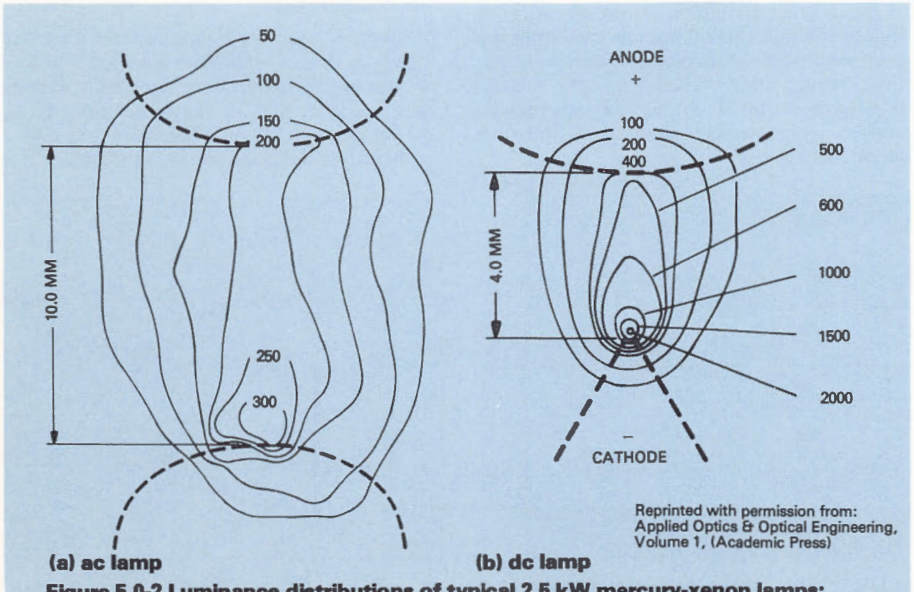


Figure 5.0-2 Luminance distributions of typical 2.5 kW mercury-xenon lamps; isoluminance contours in cd/mm².

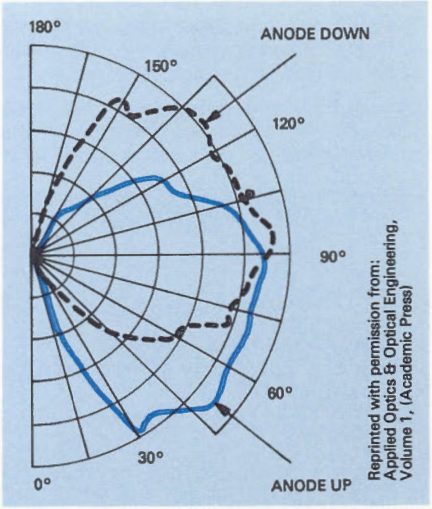


Figure 5.0-3 Relative polar intensity distribution in planes that include the arc axis for a 2.5 kW dc mercury-xenon lamp. The asymmetric distribution is caused by the unequal sizes of the electrodes.

Modulation at low frequencies can be accomplished in xenon lamps.

Spectral power distributions of the arc outputs vary greatly with type of fill and are therefore discussed in the following sections. However, all short-arc lamps emit radiation from the extremely hot tips of the tungsten electrodes and from the hot quartz bulbs. This radiation component is at much lower luminance than that of the arc itself.

Polar intensity distribution. Because of the symmetry about the axis, unjacketed two-electrode short-arc lamps have nominal uniform intensity in planes transverse to the axis. The intensity is greatest in a transverse plane through the arc, falling gradually with increasing angles above and below this plane, and then dropping sharply at angles approaching 90°, where the electrodes cause shadows. Figure 5.0-3 shows the polar distribution of radiation in planes through the axis, for a typical short-arc lamp.

Operating Characteristics

Auxiliary equipment requirements of short-arc lamps are generally more stringent than those of the enclosed-arc lamps previously described.

Requirements for dc operation of many short-arc lamps mean that rectifier power supplies are needed to convert mains ac into dc. Since the operating voltages of short-arc lamps are usually well below 100V, higher wattages can be achieved only with higher currents. Most high-power short-arc lamps are dc types, and the rectifier power supplies for those lamps must therefore be capable of rectifying and filtering large currents.

Starting-voltage requirements of short-arc lamps are generally more stringent than those of the enclosed-arc lamps previously described. Starting voltages range from 6-8kV for Colorarc lamps to as high as 50kV for xenon short-arc lamps. Special starting circuits are needed to supply such voltages. Only mercury short-arc lamps have starting voltages as low as 300-700V, and even these lamps need special restarting circuits to supply the high-voltage pulses required for hot-lamp restarting.

Current-limiting requirements of ac lamps can be satisfied by means of inductive ballasts, but such ballasts do not function on dc. For dc lamps the power supplies mentioned above are usually regulated to supply either constant current or constant power to the lamps.

The operating position recommended for many short-arc lamps, unless otherwise specified by the manufacturer, is with the arc axis in or near the vertical and, in the case of dc lamps, with the anode up. In horizontal operation, convection currents tend to cause excessive heating of the bulb directly over the arc. The foregoing statement is not inclusive; there are lamps designed for anode-down vertical operation, and others designed for horizontal operation.

Cooling considerations. Low-power short-arc lamps are designed to operate with natural convective cooling and require forced-air cooling only if the lamp enclosure prevents convective cooling. Lamps of higher wattages require forced air cooling, and some xenon lamps above about 10kW have electrodes designed to be water cooled. When forced cooling is used, appropriate sensing devices and circuits should be incorporated to cut off lamp power in case of cooling failure. Note that excessive cooling may affect the color characteristics and spectral power distributions of lamps that depend on evaporation of materials to build up to operating pressure.

Safety considerations. The high operating current densities of short-arc lamps cause high bulb temperatures (up to 900°C) and pressures (up to above 50 atmospheres). Higher-wattage short-arc lamps must therefore be operated in protective enclosures.

Mercury and metal-halide short-arc lamps have less than one atmosphere internal pressure when cold and may therefore be handled with normal care. However, xenon and mercury-xenon lamps have high internal pressures even when cold and require special care. They are shipped in protective cases and should not be removed from these cases until installed.

These lamps should be viewed directly only through filters or safety goggles that attenuate both visible and ultraviolet radiation to acceptable levels. Some lamps may emit enough ultraviolet at 184.9 nm to generate ozone, against which special precautions must be taken.

Dimming. Short-arc lamps that depend on the evaporation of metals (e.g., metal-halide lamps) to achieve operating pressures cannot be dimmed satisfactorily. Reduction of input power reduces operating pressure and stability, causing significant changes in spectral power distribution and apparent color temperature.

Xenon short-arc lamps, the spectral characteristics of which are relatively independent of operating pressure, can be dimmed to about one-third of rated input power with rather minor changes in spectral power distribution and apparent color temperature.

Factors affecting life. Short-arc lamps have life ratings in the range of 25 to 2000 hours, depending on type. End of life is not usually indicated by complete failure to operate, but by deterioration of performance to certain levels. The most significant type of deterioration is gradual bulb blackening which reduces efficacy. Either of two criteria may be applied to indicate end of life: (1) for constant input power, when lumen output falls below a specified percentage of initial lumen output; and (2) for constant lumen output, when input power required to maintain that output rises above a specified input power.

Bulb blackening not only reduces lumen output, but the absorption of radiation by the black deposit raises the bulb temperature, and this may cause failure of the bulb and/or quartz-metal seals. Other symptoms which may indicate approaching end of life are excessive electrode erosion, arc instability, and hard starting. Life can be shortened by inadequate cooling, improper operation, and repeated restarts before full warm-up.

Percent of total radiated power in the UV, visible and near-IR. Figure 5.0-4 lists the percent of total power radiated in the ultraviolet, visible, and infrared bands for various types of short-arc lamps.

5.1 Mercury Short-Arc Lamps

Mercury short-arc lamps contain a starting gas (e.g., argon) to facilitate starting at voltages as low as 300 to 700V. After the initial start there is a warm-up time of several minutes during which the mercury vaporizes and the pressure, voltage, and light output increase. These

LAMP TYPE	UV 200NM TO 380NM %	VISIBLE 380NM TO 760NM %	NEAR-IR 760 NM TO 1400 NM %
MERCURY (1 KW AC)	14	46	40
MERCURY-XENON (1 KW AC)	17	47	36
XENON (1 KW AC)	4	30	66
METAL-HALIDE (HMI) (200W AC)	9	61	30
COLORARC (300W DC)	4	56	40

Figure 5.0-4 Percent of total radiated power in the UV, visible, and near-IR for various short-arc lamps.

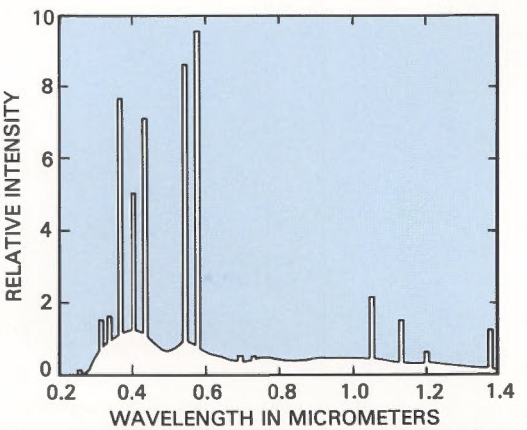


Figure 5.1-1 SPD of typical mercury short-arc lamp.

parameters stabilize when the mercury is completely evaporated. A cooling time of several minutes is required for restarting at 300-700V.

Figure 5.1-1 shows that the spectral power distribution of mercury short-arc lamps is significantly different from that of lower-pressure mercury lamps. At the higher operating temperatures and pressures of the mercury short-arc lamp, the characteristic mercury lines are broadened (except for the 253.7 nm ultraviolet line which is almost completely reabsorbed), a smaller proportion of the radiation is in the ultraviolet and a greater proportion is in the visible, and the continuum increases relative to these lines. The color of the light output is the characteristic bluish-green of mercury arc lamps with correlated color temperatures in the range of 7000K to 10,000K. Luminous efficacy is in the order of 50 lm/W.

5.2 Mercury-Xenon Short-Arc Lamps

The warm-up time of several minutes for mercury short-arc lamps can be reduced to 1-2 minutes, and the cooling time before restarting can be reduced from several minutes to nearly zero, by adding xenon at a pressure above 1 atmosphere.

The resulting mercury-xenon short-arc lamp requires high-frequency starting-voltage pulses in the range of 30-50 kV but can be restarted immediately with pulses of the same amplitude.

Figure 5.2-1 shows that the spectral power distribution of mercury-xenon short-arc lamps is similar to that of the mercury lamp, except that the xenon adds continuum radiation as well as some weak lines in the 800-1000nm near-infrared region. The color of the light output is still the characteristic bluish-green of mercury lamps, the correlated color temperature is still in the range of 7000K to 10,000K, and the luminous efficacy is in the range of 50-55 lm/W.

5.3 Xenon Short-Arc Lamps

Xenon short-arc lamps require 50kV starting-voltage pulses. The light output reaches about 80% of operating value almost immediately, and full warm-up requires 5 to 10 minutes. No cooling time is required before re-starting because hot-lamp restarting is possible with the starting-voltage pulses.

The spectral power distribution (Figure 5.3-1) is continuous from the ultraviolet to the infrared, with some strong lines in the 800 to 1000nm near-infrared region. The color quality of the light output is similar to that of daylight with a correlated color temperature of about 6000K. Efficacies range from about 30 lm/W at low wattages to more than 50 lm/W at several kilowatts.

5.4 Metal-Halide Short-Arc Lamps

Metal halides and starting gases can be added to the atmospheres of high-pressure mercury short-arc lamps for the same reasons that they have been added to medium pressure metal-halide lamps such as Metalarc lamps. Metal-halide short-arc lamps have light outputs with good color rendering qualities and high luminous efficacies.

High-Color-Temperature Lamps

Holmium/dysprosium-iodide short-arc lamps (e.g., Brite-Arc™ or HMI) are standard in sizes ranging from 200W with 10mm arc length to 4000W with 35mm arc length. They require starting-voltage pulses in the range of 10-20kV, and initial warm-up times of 2-3 minutes. Hot-lamp restarting is possible with starting voltages in the order of 20-40kV.

These lamps have arc luminances of about 100cd/mm², and efficacies in the range of 80-100 lm/W. Life is in the order of 500-1000 hours, and lumen maintenance is about 90% at 600 hours. Correlated color temperature is about 5600K initially, but it decreases about 1K per hour so that useful life in critical color applications may be as low as 200 hours. Figure 5.4-1 shows the SPD of a typical holmium/dysprosium-iodide short-arc lamp.

Low-Color-Temperature Lamps

Indium/thallium/sodium-iodide short-arc lamps (e.g., Thorn CSI lamps) are made in ratings of 400W with 9mm arc length and 1000W with 15mm arc length. These lamps are of compact single-ended construction. They require starting-voltage pulses of about 10kV, and

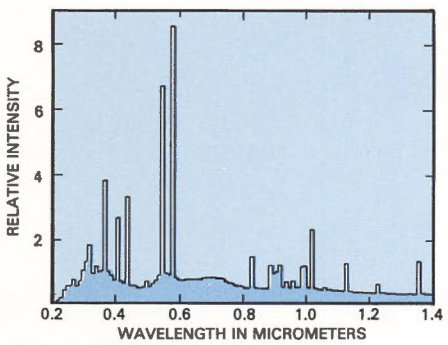


Figure 5.2-1 SPD of typical mercury-xenon short-arc lamp.

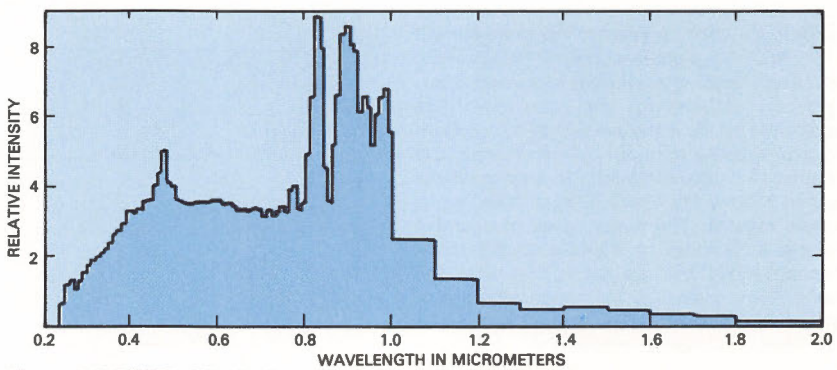


Figure 5.3-1 SPD of typical xenon short-arc lamp.

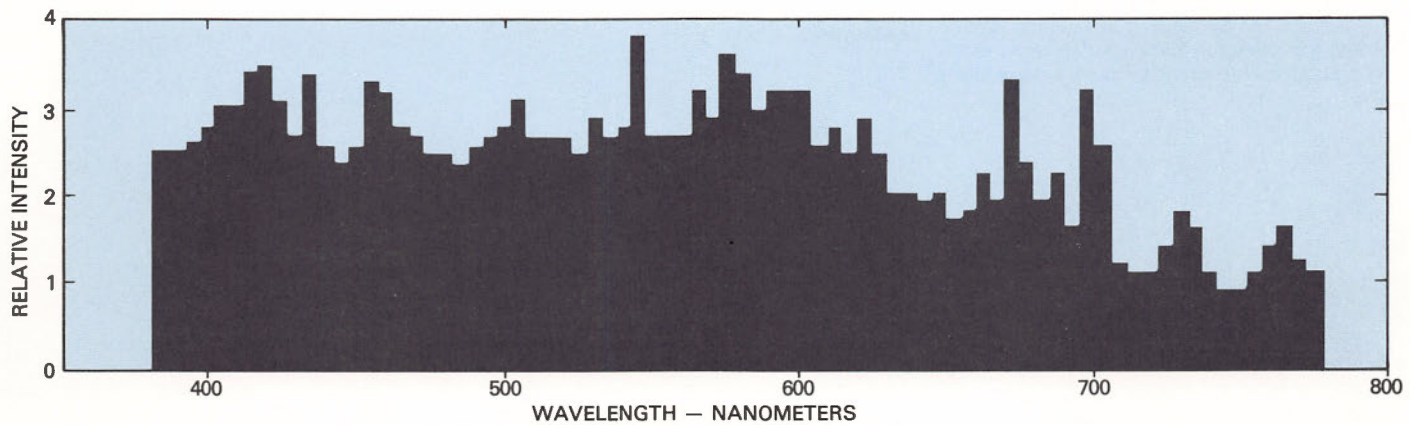


Figure 5.4-1 SPD of a typical (holmium-dysprosium-Iodide) short arc lamp (Brite-Arc™ or HMI).

can be restarted with pulses of the same level after a cooling period of 2-10 minutes. Color-rendering quality and efficacy are similar to those of holmium/dysprosium-iodide short-arc lamps. Figure 5.4-2 shows the spectral power distribution of a typical indium/thallium/sodium-iodide short-arc lamp. Life of the basic lamp is about 200 hours; this is increased to about 1000 hours by enclosure in an outer jacket containing an inert gas fill.

5.5 Colorarc Short-Arc Lamps

Colorarc lamps are small dc short-arc lamps filled with indium triiodide. In the most common form the arc tube is mounted within an ellipsoidal cold-mirror reflector of about 3" diameter (Figure 5.5-1). The lamp is positioned with its 3mm arc gap at the near focus of the reflector which focuses the light on the far focus. The far focus is near the film gate and aperture of a 16mm film projector.

Colorarc lamps are only available in nominal 300W ratings. The luminance over the principal axis is relatively constant at about 400cd/mm², and initial efficacy is about 45 lm/W. These lamps give greater screen brightness and whiteness than incandescent projection lamps of much greater wattage. The rated color temperature is 5000K, but the range for specific lamps is 4000K to 7000K, due to circuit, lamp, and cooling variables. The spectral power distribution is shown in Figure 5.5-2.

The average rated life of a Colorarc 300 lamp is 50 hours when operated at the rated current of 7.7Adc from a power supply of recommended design which provides the required dc current, current-limiting, and starting-voltage pulses. Rated life is the average of a large sample and includes both operable and inoperable failures. An operable failure is a lamp whose screen lumens fall below 50% of rated initial screen lumens. The major cause of operable failures is build-up of a white devitrification deposit inside the arc tube, first near the cathode and later near the anode, which progressively reduces total light output and causes non-uniform screen illumination. An inoperable failure is a lamp that cannot be started, usually as a result of a seal failure. Note that excessive cooling causes variations in light output and life. The voltage can be reduced as much as 30% resulting in life up to 300 hours. However the light output decreases and becomes excessively blue.

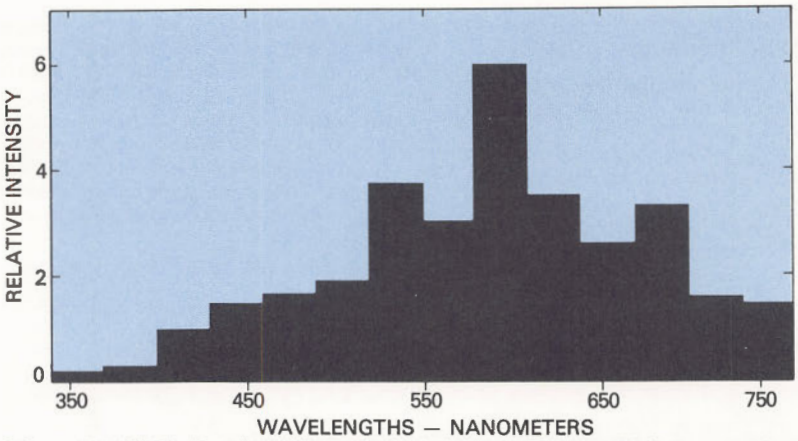


Figure 5.4-2 SPD of a 1 kW CSI (indium/thallium/sodium-iodide) short-arc lamp.

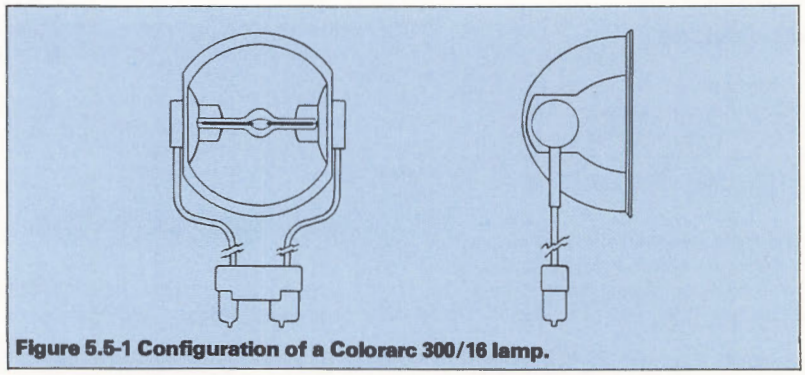


Figure 5.5-1 Configuration of a Colorarc 300/16 lamp.

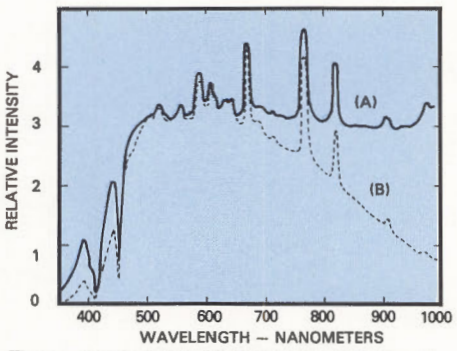


Figure 5.5-2 SPD of Colorarc 300 lamp. A-arc; B-after reflection from dichroic reflector.

6.0 Electronic Flash Lamps

Electronic Flash lamps or flashtubes are cold-cathode arc lamps designed to produce light flashes of short duration and high intensity when electrical energy stored in external capacitors is discharged through those lamps in the form of current pulses. The peak intensities of the light pulses from these lamps can be much higher than the intensities of the outputs from most continuously-operating light sources. There are two major types; xenon flashtubes which are discussed in Section 6.1, and strobotrons which are discussed in Section 6.2.

6.1 Xenon Flash Tubes

Individual types of flashtubes can be designed to operate over restricted ranges within the present design limits of energy inputs from 10^{-2} to 10^{6} joules per pulse, pulse widths from one to 10^{3} microseconds, and repetition rates from single shot to 5×10^{3} pulses per second (pps.). As a result of the extremely wide range of possible operating parameters, flashtubes can be used not only as light sources for exposure in micro/photo/repro-graphic applications, but in thermal fusing and photochemical processes and as light-pump sources for lasers.

Principles of Operation

Figure 6.1-1 is a generalized block diagram showing the basic elements of a typical flashtube operating circuit. These comprise a charging circuit, a discharge circuit, and a triggering circuit. Energy-storage capacitor **C** is common to both the charging and discharge circuits. The charging circuit contains a high-voltage dc supply which, through charging impedance **Z**, charges energy storage capacitor **C** to the voltage **V**. The discharge circuit contains the flashtube which is connected across capacitor **C** and thus has the voltage **V** impressed across it. The voltage **V** is less than the self-ionization voltage of the flashtube which therefore does not fire until the triggering circuit applies a trigger pulse to ionize the gas in the flashtube. Capacitor **C** then discharges its stored energy through the ionized gas to generate a brief, intense flash of light. As the capacitor discharges, the voltage across the flashtube drops until it falls below the maintaining voltage of the arc, and the flashtube is extinguished. Capacitor **C** then recharges through charging impedance **Z** to the voltage **V** at which the flashtube can again be fired.

Physical Characteristics

Typical Construction Features

Configuration. Flashtubes are usually long arc tubes of relatively small diameter, with a current-carrying electrode sealed into each end and with a third electrode (which is usually external) for triggering the discharge. These arc tubes may be linear, or (if it is desired to compress a greater light-producing length into a smaller effective source area) they may be formed into U, L, C or serpentine shapes, or into helices, loops or flat spirals. The tubes are sometimes enclosed in outer jackets with bases. Figure 6.1-2 shows some typical flashtube configurations.

Bulb materials for flashtubes must be capable of withstanding high thermal shock and must have high electrical resistivity even at the highest bulb operating temperatures. The most frequently used materials are fused silica and borosilicate glasses, although other high-temperature glasses such as aluminosilicate, 96% silica, and alumina may be used. Borosilicate glasses are used for temperatures up to 230 °C and bulb wall loadings up to 0.5 W/cm². Fused silica is used for temperatures up to 900 °C and wall loadings up to 15 W/cm²; however, the silica-metal seals of the electrode leads become unreliable at loadings in the order of 2W/cm² with natural convection cooling, so that forced-air cooling is required for higher loadings.

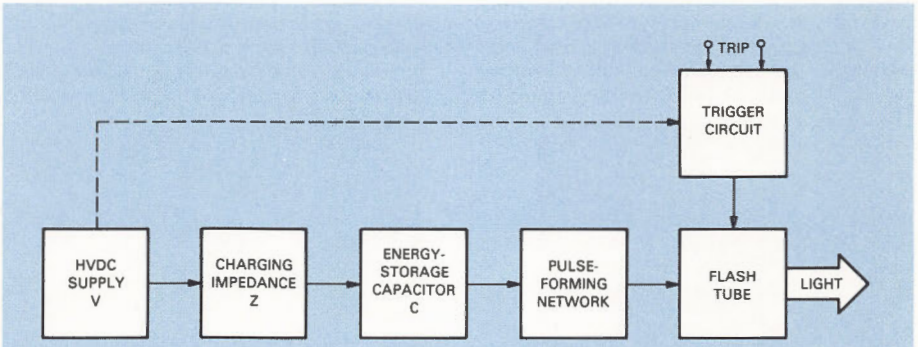


Figure 6.1-1 Generalized block diagram of flashtube operating circuit.

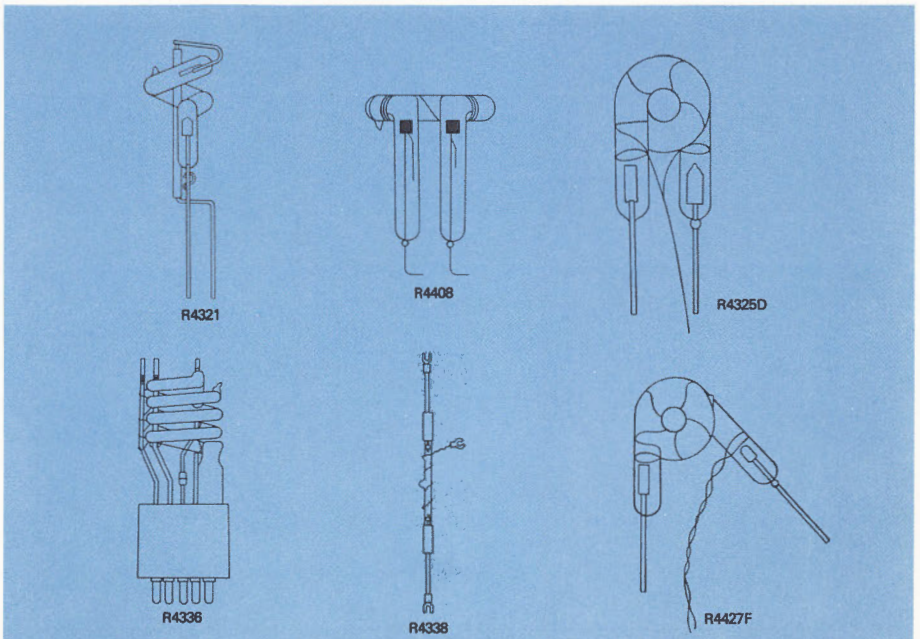


Figure 6.1-2 Typical flashtube configurations.

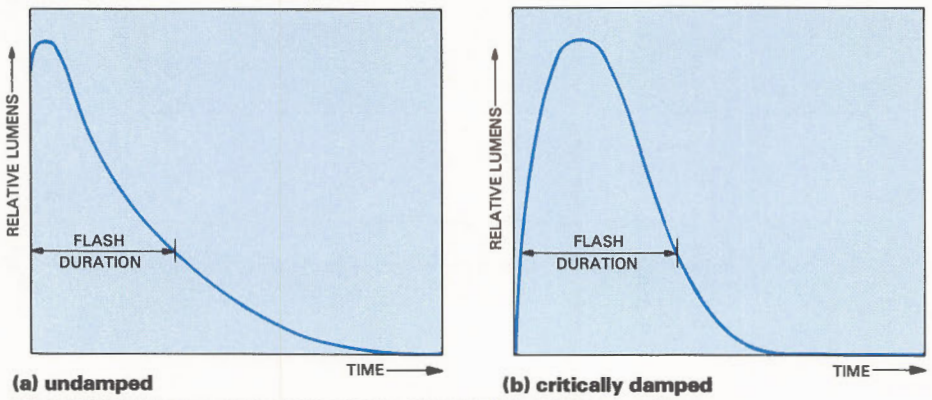
Such cooling permits increased loadings up to 40 W/cm². For applications in which the average power is extremely high, water cooling may be employed. This allows wall loading as high as 300 W/cm².

The bore (internal diameter) of the glass tubing is often desired to be as small as possible for optical considerations. However, the bore must be sufficiently large so that the energy and power per unit wall area do not exceed the degradation threshold of the glass. Too small a bore may cause short life and perhaps even catastrophic failure. Too large a bore, although permitting long life, will cause poor efficiency because the volume is not adequately filled with the arc plasma. In a properly-designed flashlamp the bore and arc length are chosen to maximize life while at the same time giving the lamp an impedance which will match that of the discharge circuit, thus producing an optimum discharge waveform at the desired pulse width.

The arc length, or distance along the tube between the anode and cathode faces, affects a number of operating parameters such as trigger requirements, self-ionization voltage, radiant efficiency, and impedance. The arc length must be great enough to prevent self-ionization of the flashtube at the rated supply voltage, but arc lengths greater than this minimum will increase the trigger energy requirements. The flashtube impedance R_F, which affects the duration of the flash, is directly proportional to arc length.

Cathodes (negative electrodes) are designed to emit electrons when cold. For low-energy and low-power applications inexpensive cup-shaped cathodes, coated with low-melting-point emitters such as barium or strontium, may be satisfactory. More commonly, sintered tungsten pellet cathodes impregnated with emissive materials, or double-coil cathodes made of thoriated tungsten wire, are used.

Anodes (positive electrodes), which absorb free electrons from the discharge, are designed to dissipate the heat generated by the kinetic energy of those electrons upon impact. For high-energy and high-power applications, anodes are usually fabricated from high-purity solid tungsten. For lower-energy applications, other materials such as tantalum may be used to reduce cost. In some cases cathodes are used at both ends of the lamp to maintain lamp life in those applications where the discharge current may reverse direction. However, during the manufacture of the lamp, usually only one of the electrodes is processed as a cathode. The user is then cautioned to install the lamp with the proper polarity.



(a) undamped **(b) critically damped**

Figure 6.1-3 Time-light characteristics of typical flashtube circuits.

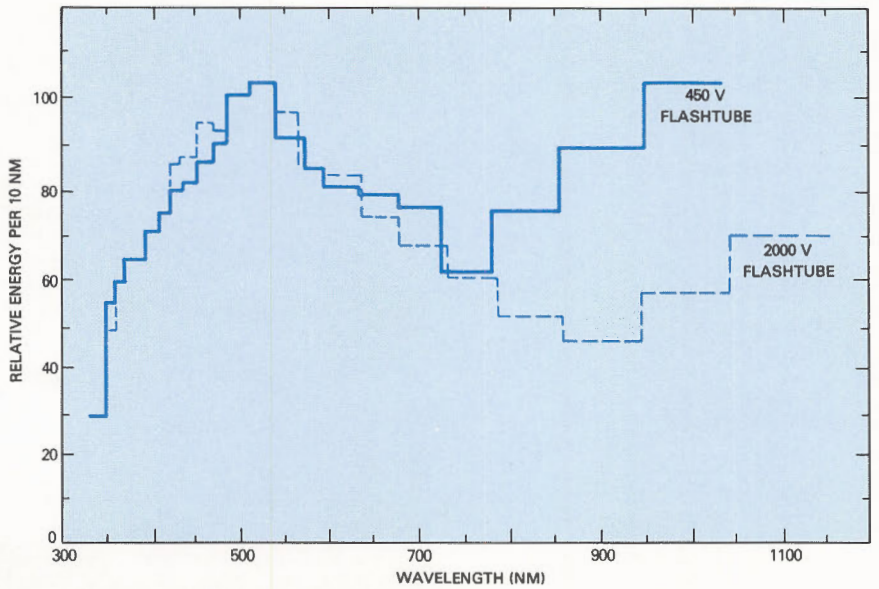


Figure 6.1-4 Spectral energy distributions of typical xenon flashtubes.

Electrode seals must be capable of withstanding the thermal and mechanical shock of the flash discharge without failure. The sealing techniques employed will depend mainly on the bulb material (e.g., glass or fused silica) and on the maximum energy and average power rating. High-temperature operation may require cooling of the external metal parts of the electrode and the region of the seal.

Trigger electrodes are usually completely external. One type of external trigger electrode is an invisible conductive coating on the outside of the arc tube wall; another is a fine wire wrapped around the arc tube.

Gas-fill composition. In addition to being chemically inert, the noble gases (helium, argon, krypton, neon, and xenon) are most effective in converting the energy of free electrons into continuum radiation. Of the inert gases, xenon is generally the best fill for flashtubes because the heavier xenon atoms conduct the least heat to the arc-tube wall and because xenon has higher output/input efficiencies in most applications. These efficiencies range from 25 to 60% depending on lamp construction and operation conditions, and generally increase with power density. Xenon, therefore, is almost always used as the fill gas in flashtubes, and the other inert gases are used only when their electrical, spectral, or thermophysical properties are important. For example, krypton is sometimes used in low-energy flashlamps for pumping Nd:YAG lasers, because one of its strong infrared lines matches one of the absorption bands of the laser material.

Gas additives are frequently used to improve flashtube performance. For example, hydrogen may be added as a quencher to eliminate undesired effects such as afterglow and self-ionization.

Gas-fill pressure has significant effects on circuit cost, maximum discharge energy, and efficiency. For example, pressures of 50-100 torr (.06-.13 atm) permit use of lower operating voltages and thus of lower-cost circuits but are not suited for high-energy discharges because of electrode sputtering which causes rapid tube blackening, reduced light output, and shortened life. Pressures of 100-400 torr (.13 - .53 atm) are optimum for high-energy discharges, and pressures of 400-700 torr (.53 - .93 atm) give greater efficiency but require higher trigger energies.

Illuminating Characteristics

Time-light characteristics of flashtubes usually exhibit a rapid rise to the peak value and a somewhat slower decay to the level at which the arc is extinguished. Figure 6.1-3a shows the time-light characteristics of a flashtube with a simple undamped capacitor discharge circuit, and Figure 6.1-3b shows the time-light characteristics of a flashtube with a discharge circuit that has been critically damped by insertion of

the proper value of inductance into the discharge circuit. The shape of the light output waveform closely resembles that of the flashtube current waveform.

Flash duration is usually defined as the time between two points on the time-light characteristic that are at one-third the peak level. Approximately 67% of the radiant energy of the flashtube is emitted during this period. The flash duration is indicated in the time-light characteristics of Figure 6.1-3. In Figure 6.1-3a, the time-light characteristic of a simple undamped capacitor-flashtube circuit, the flash duration is given by:

$$t = RC/2 \quad \text{, where} \qquad \text{(eq. 6.1-1)}$$

t = power time constant, μsec

R = effective resistance of the discharge circuit, ohms

C = energy-storage capacitance, μF.

In a well-designed circuit, the effective resistance of the discharge circuit is almost entirely that of the flashtube itself. Although this resistance is highly nonlinear, it can be estimated (for xenon flashtubes) from:

$$R = \rho\,(L/A) \quad \text{, where} \qquad \text{(eq. 6.1-2)}$$

R = effective resistance of flashtube, ohms

ρ = xenon plasma resistivity, typically .015 - .030 ohm-cm.

L = arc length, cm

A = arc cross-sectional area, cm^2

Total light output in lumen-seconds is usually specified for the condition of operation at maximum watt-second ratings.

Efficiencies of flashtubes are generally measured in lumen-seconds per watt-second (lm-sec/W-sec) or lumen-seconds per joule (lm-sec/J), because of the pulsed operation of these tubes. These units are analogous to the lumens per watt (lm/W) in which the efficacies of continuously-operating sources are stated. The efficiencies of xenon flashtubes range from 20-50 lm-sec/W-sec depending on current density, fill pressure, and physical dimensions of the flashtube. High-power xenon flashtubes with fill pressures greater than 400 torr have efficiencies of approximately 40 lm-sec/W-sec.

Spectral energy distribution. Since flashtubes are not continuous sources, their spectral distributions, like those of chemical flashlamps, are specified in terms of energy instead of power. Typical xenon flashtubes emit about 10% of their total radiant energy in the ultraviolet (below 400nm), about 30% in the visible (400 to 700nm), about 40% in the near infrared (700 to 1000nm), and about 20% in the middle and far infrared (above 1000nm). These percentages are affected by the bore, the current density, and the bulb material. Figure 6.1-4 shows the spectral energy distribution of two typical xenon flashtubes for photographic applications. Although the design operating voltages (450 and 2000V) are quite different, the spectral energy distributions are nearly identical in the visible. The major difference is in the infrared, where the lower-voltage flashtube has the greater output.

Color temperature. The apparent color temperature of most xenon flashtubes for photographic applications is in the range of 5000K to 7000K. This is an exceptionally close match to the 5500K color temperature of daylight (sun plus sky). Moreover, the spectral output of xenon flashlamps is continuous over the visible spectrum. For those reasons xenon light is an almost perfect substitute for daylight, rendering exceptionally high color fidelity in photographs. In some cases, color-correcting fillers can improve the match by lowering the apparent color temperature slightly.

In very-high-energy or very-short-pulsewidth applications, the color temperature of xenon flashlamps increases. For example, certain xenon flashlamps designed for pumping dye lasers have measured color temperatures exceeding 20,000K.

Exposure guide numbers for flashtube photography depend on the flashtube efficiency, operating conditions, reflector parameters, and film speed. An approximate guide number can be calculated as follows:

$$GN = \sqrt{0.005 \times M \times S \times E \times (L/W)} \qquad \text{(eq. 6.1-3)}$$

, where

GN = guide number

M = reflector factor

S = ASA or ANSI film speed

E = energy in discharge, J or W-sec.

L/W = lamp efficacy, lm-sec/W-sec.

GN, the guide number calculated from the formula above, is equal to the product of the lamp-to-subject distance in feet and the f-number of the camera lens. Once the guide number is know, the camera lens f-number setting for optimum exposure can be determined for any lamp-to-subject distance from f-number = **GN**/(distance).

M, the reflector factor, depends on reflector shape, diameter, and finish. The value of **M** ranges from 10 to 15 for reflectors with narrow (25° to 40°) beamspreads, from 6 to 8 for reflectors with 50° beamspreads, and from 3 to 5 for reflectors with beamspreads greater than 50°.

L/W, the flashtube efficiency, ranges from as low as 10-15 lm-sec/W-sec for lightly-loaded flashtubes, through a typical value of 35 lm-sec/W-sec for most flashtubes, to as high as 50 lm-sec/W-sec for heavily-loaded flashtubes.

Operating Characteristics

Flashtube Rating Parameters

The flashtube rating parameters defined below are collected from the technical literature and from the published data of various manufacturers. These terms are included to give insight into the various factors that affect performance and life. At the time of this publication, the American National Standards Institute (ANSI) has not yet recommended a standardized set of parameters for use by all flashtube manufacturers, so that the published data of any manufacturer may include some but not others of the following parameters.

Single-shot (or single-pulse) expolsion energy, Ex, in joules (J) or watt-seconds (W-sec) is the input energy that will cause wall explosion and destroy the flashtube in one discharge. The single-pulse explosion energy varies linearly with pulse width as shown in Figure 6.1-5 for typical flashtubes. Such graphs, which are determined experimentally by the flashtube manufacturer for each type, represent an upper limit of energy input that may be used as a design guide rather than as an operating parameter.

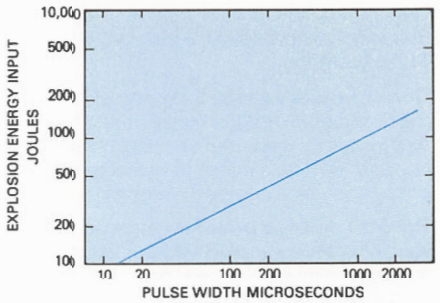


Figure 6.1-5 Single-pulse explosion energy versus pulse wide for a typical flashtube.

Maximum energy input Emax, in watt-seconds or joules, also called maximum watt-seconds, is the largest actual energy input permissible for any single flash. Energy inputs in excess of this rating can cause crazing of the arc tube wall, failure of the electrode seals, and reduced life. The energy input for any flash is:

$$E = \tfrac{1}{2}\,CV^2 \quad \text{, where} \qquad \text{(eq. 6.1-4)}$$

E = energy input, J or W-sec.

C = energy-storage capacitance, F

V = voltage on capacitor before firing, V

Maximum power dissipation, Pmax, permissible for reliable operation and long life under specified cooling conditions, is also called **maximum power input** and **maximum average power.** The average power input to a flashtube is equal to the product of energy input **E** per flash (joules or watt-seconds) and the number of flashes per second. This average input power is converted into both radiant power and heat, and the maximum allowable value of average input power is limited by the ability of the flashtube to dissipate that heat. The heat-dissipating ability of the flashtube is greatly affected by the type and rate of cooling, so that the cooling conditions must be specified along with the maximum average power rating.

Since the maximum average power input rating is based on the ability of the flashtube to dissipate heat, it must be reduced under condi-

tions such as high ambient temperatures or use in small enclosures that restrict natural convective cooling. The maximum average power rating may be exceeded for brief periods if other ratings are not exceeded.

If the maximum average power rating is known, the maximum allowable number of flashes per second can be calculated for any energy input per flash as the ratio of the maximum average power rating to the energy input per flash.

Maximum flashing rate at maximum watt-seconds. The product of flashing rate in flashes per second and energy input in watt-seconds is equal to the average power input. If the product of maximum flashing rate and maximum watt-seconds is less than the maximum power input, the flashing rate may be increased to the value corresponding to the maximum power input.

Maximum anode voltage is the highest voltage, consistent with safe lamp operation, that can be applied across the main electrodes of the flashtube.

Design anode voltage is the voltage at which the flashtube is designed to operate. Maximum energy ratings are based on design anode voltage and must be reduced at higher anode voltages to limit peak current through the flashtube.

Hold-off voltage is the maximum anode voltage that can be applied without causing self-flashing. Hold-off voltage decreases at high temperatures or high ambient light levels and also gradually decreases near the end of tube life.

Minimum starting voltage or minimum capacitor voltage is the lowest anode voltage at which the flashtube will fire reliably when the specified trigger voltage is applied. For most flashtubes this voltage is approximately equal to 300 volts plus 100 volts per inch of arc length for external triggering, and approximately 60 volts per inch of arc length for series triggering.

Minimum trigger pulse is the specified voltage level that the trigger pulse must exceed for a specified duration in order to cause reliable triggering.

Light output at maximum watt-seconds per flash is usually expressed in lumen-seconds (lm-sec); the light output for some straight flashtubes and for reflector lamps may be expressed in horizontal candlepower-seconds or in beam horizontal candlepower-seconds.

Efficacy is the light energy output divided by the electrical energy input, and is expressed in lumen-seconds per watt-second (lm-sec/W-sec). The efficacy of a given flashtube varies with loading and falls off considerably at low loadings.

Life is stated in number of flashes before light output is reduced to a specified percentage (usually 50%, sometimes 70%) of initial light output. Figure 6.1-6 shows life versus $\mathbf{E/E_x}$, the ratio of energy input per flash to the single-shot explosion energy. The sloping line is the operating region in which life varies inversely as $\mathbf{E/E_x}$ and in which life can be extended by reducing $\mathbf{E/E_x}$.

When flashtubes are operated within their maximum average power ratings, their life varies roughly as the fourth power of pulse width and inversely with energy per flash. If pulse width and energy input **E** per flash are both known, flashtube life can be determined from Figures 6.1-5 and 6.1-6 as follows: the pulse width is used in Figure 6.1-5 to determine the single-shot explosion energy $\mathbf{E_x}$; the energy input **E** per flash and the explosion energy $\mathbf{E_x}$ are then used to calculate the ratio $\mathbf{E/E_x}$, from which the life can be found in Figure 6.1-6.

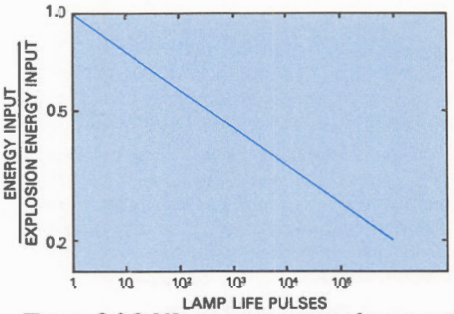


Figure 6.1-6 Life versus energy input per flash for a typical flashtube.

Under operating conditions approachng specified limits, flashtube life may be significantly shorter than that determined above. At high average and/or peak power inputs, electrode material may be sputtered onto the bulb wall, and may ultimately reduce light output to below the specified end-of-life level (usually 50%, sometimes 70% of initial light output). At high peak power densities, small amounts of the bulb wall may be vaporized, condensing later as a white crystalline coating on the bulb wall. This coating absorbs energy from the flash, increases the loading on the bulb wall, and reduces the light output. As this coating builds up with successive flashes, the wall loading may increase to a level at which catastrophic failure results, or the light output may fall below the limit specified for end of life.

Typical Operating Circuits

Every flashtube operating circuit consists of three functional circuits: the charging circuit and the discharge circuit, which share the energy-storage capacitor **C1,** and the trigger circuit. The most common types of trigger circuits employ external triggering as shown in Figure 6.1-7, or series triggering as shown in Figure 6.1-8. The various functional circuits are discussed below.

Charging Circuits

The charging circuit consists of a high-voltage dc supply, charging impedance **Z,** and energy-storage capacitor **C1.** The high-voltage dc supply is shown as a block only, because of the large number of possible circuit variations. The high-voltage-dc supply may be a high-voltage dry battery, a low-voltage-dc to high-voltage-dc converter operating from a low-voltage replaceable or rechargeable battery, or a line-voltage-ac to high-voltage-dc rectifier. The first two arrangements permit complete portability, while the third requires access to ac lines. A common hybrid arrangement combines a line-voltage-ac to low-voltage-dc rectifier and a low-voltage-dc to high-voltage-dc converter, with a rechargeable battery connected across the low-voltage-dc bus between the output of the rectifier and the input of the converter. This arrangement permits operation either from ac lines or from the rechargeable battery.

Charging impedance Z is usually a resistor connected in series between the output of the high-voltage-dc supply and the energy-storage capacitor. Charging impedance **Z** limits the maximum surge current from the high-voltage-dc supply, the charging rate of capacitor **C1,** and the rate at which the flashtube can be fired; and it permits the flashtube to deionize and become extinguished each time it is fired.

Note that a significant proportion of the energy delivered by the high-voltage dc supply is dissipated as heat in the charging resistor. This energy may be saved by using a constant-current-dc supply and eliminating the charging resistor, thus permitting more flashes before replacement or recharging of the battery is required.

Energy-storage capacitor C1 must be rated for the highest expected charging voltage, must have low dielectric losses, and must be capable of withstanding the stress of many cycles of charge and discharge. Typical energy-storage capacitors have low-loss paper or plastic dielectrics.

Discharge Circuits

The discharge circuit is essentially a pulse-forming network comprising energy-storage capacitor **C1,** the flashtube, and series inductance **L.**

Undamped discharge circuits. In low-cost flashtube operating circuits the series inductance **L** may be merely the distributed self-inductance of the connection between the capacitor and the flashtube, and the discharge circuit is therefore almost completely undamped as shown in Figure 6.1-3a.

Critically-damped discharge circuits. In higher-quality flashtube operating circuits, **L** is a discrete inductance, usually of such value as to cause critical damping of the discharge circuit as shown in Figure 6.1-3b. The inductance **L** may be that of the inductor shown in Figure 6.1-7, or it may be the saturated inductance of the secondary winding of the series trigger pulse transformer shown in Figure 6.1-8.

Trigger Circuits. The voltage developed across the energy-storage capacitor and the flashtube by the charging circuit causes a voltage gradient along the flashtube between the two main electrodes. This voltage gradient is normally less than that required to ionize the gas and cause self-flashing. The flashtube therefore does not fire until the trigger circuit delivers a trigger voltage pulse that causes the total voltage gradient to exceed the breakdown voltage of the gas along some path, usually between one main electrode and some point on the inner wall near the trigger electrode on the outside of the tube. A thin spark streamer of ionized gas forms along this breakdown path, and the wall-end of the streamer moves along the inner wall until it reaches and transfers to the other

main electrode. The thin streamer then provides an initial conductive discharge path between the main electrodes. The energy-storage capacitor then begins to discharge its energy through the streamer, which grows in diameter (at a rate determined by the constants of the discharge circuit) until the ionized gas fills the flashtube. In order to cause these phenomena to occur reliably, the trigger circuit must deliver a trigger pulse of proper peak voltage, polarity, duration, energy content, and shape. The two major types of triggering circuits, and the trigger-pulse requirements which those circuits must satisfy, are discussed below.

External trigger circuits, such as that shown in Figure 6.1-7, apply the high-voltage trigger pulse between the external trigger electrode and one main electrode. Although this main electrode is a common point between the trigger circuit and the discharge circuit, the two circuits are otherwise isolated so that the discharge current from energy-storage capacitor **C1** does not flow through trigger-pulse transformer **T.** The trigger-pulse transformer, therefore, may be small and inexpensive.

For reliable external triggering of xenon flashtubes, the charging voltage should be at least 300 volts plus 100 volts per inch of arc length. Note that since the trigger voltage is applied to the external trigger electrode, this method of triggering is not reliable at high humidities or high altitudes unless the flashtube is enclosed within a sealed outer envelope.

Series trigger circuits, such as that shown in Figure 6.1-8, use the flashtube trigger electrode as a ground plane tied to the common between the trigger circuit and the discharge circuit, and employ a trigger-pulse transformer with secondary winding in series between the high side of energy-storage capacitor **C1** and the flashtube. The voltage across the flashtube is thus the algebraic sum of the voltage across the energy-storage capacitor and the trigger voltage across the secondary winding of the pulse transformer. This permits reliable triggering even with main discharge capacitor voltages as low as 60 volts per inch of arc length. When the flashtube is triggered, the discharge current saturates the pulse transformer core so that the saturated inductance of the transformer secondary winding provides the pulse-forming inductance of the discharge circuit. Since the trigger pulse transformer is required to have isolated primary and secondary windings, and the secondary winding is required to carry the discharge current and (when the core is saturated) to supply the pulse-forming inductance, the pulse transformer is usually larger and more expensive than the trigger pulse transformer in external triggering circuits. Sometimes it is not economical to design a series trigger pulse transformer which has the saturated secondary inductance required for critical damping while satisfying all other circuit requirements.

Series trigger circuits are sometimes more desirable than external trigger circuits because they permit triggering with lower capacitor-charging voltages and because they can be completely encapsulated for operation at high humidities and high altitudes.

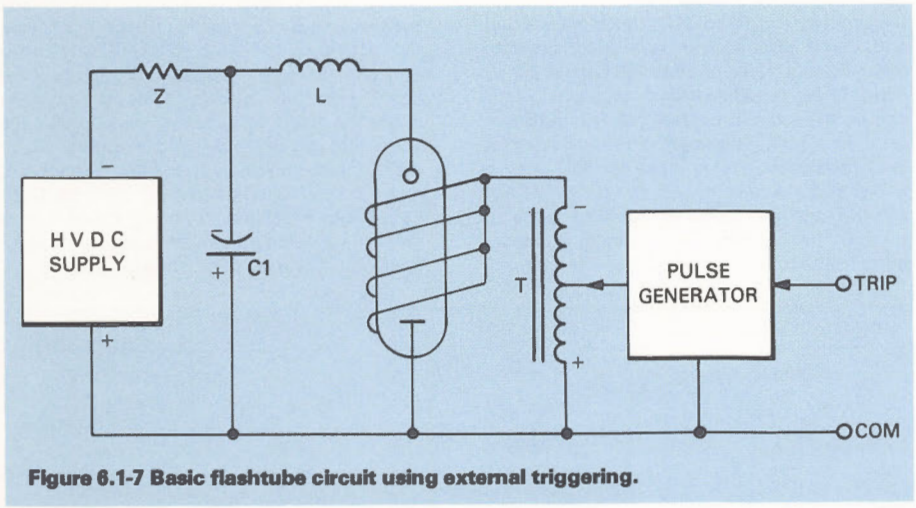


Figure 6.1-7 Basic flashtube circuit using external triggering.

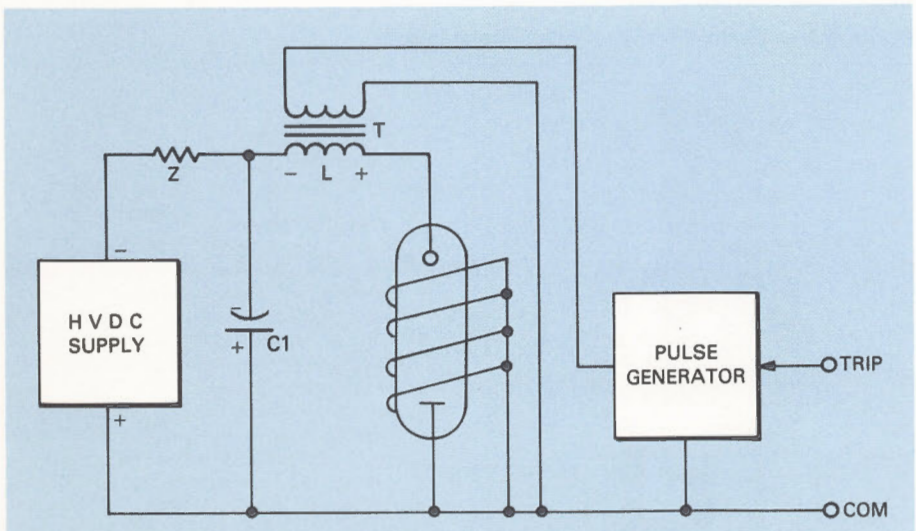
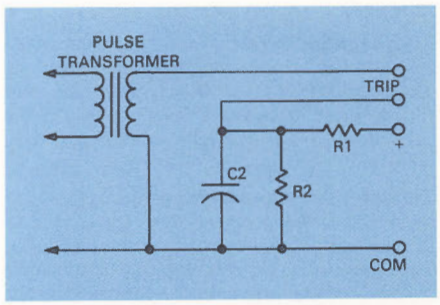


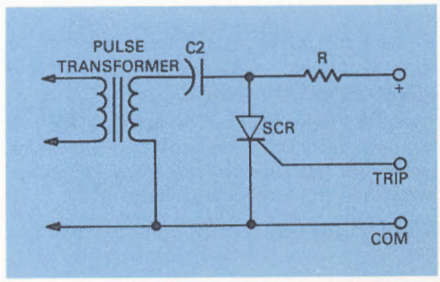
Figure 6.1-8 Basic flashtube circuit using series triggering.

Pulse-generating circuits for driving the trigger pulse transformers in Figures 6.1-7 and 6.1-8 may consist entirely of passive components, as shown in Figure 6.1-9a, or may contain active switching devices like the silicon controlled rectifier shown in Figure 6.1-9b.

The circuit of Figure 6.1-9a is usually used only in low-energy flashtube circuits such as those built into amateur cameras, and may be tripped directly by shutter-actuated switch contacts.



(a) Circuit with passive components for low-energy flashtubes



(b) Circuit with SCR for low-or high-energy flashtubes

Figure 6.1-9 Typical pulse-generating circuits for driving trigger pulse transformers.

This circuit is not recommended for high-energy applications because repeated actuation would cause deterioration of the switch contacts.

The SCR circuit of Figure 6.1-9b may be used either in low-energy or high-energy applications. The energy required to fire the SCR is so low that no deterioration of trip switch contacts occurs.

Trigger Pulse Requirements

It is important to match the parameters of the trigger pulse to the operational requirements of the flashtube. Trigger-pulse parameters are discussed below.

Trigger-pulse peak voltage must be large enough to initiate the spark streamer even at the lowest charging voltage that will be encountered in operation.

Trigger-pulse duration must be long enough to maintain the spark streamer until the main discharge becomes self-sustaining. Trigger-pulse duration is usually defined as the time between two points on the pulse which are at 10% of the peak value.

Trigger-pulse energy must be large enough to cause reliable firing, but not large enough to cause damage. Insufficient trigger pulse energy may cause occasional misfiring or complete failure to flash. Excess trigger pulse energy may cause external arcing or even puncture of the tube wall.

Trigger-pulse polarity is an important consideration in reliable triggering of flashtubes. The polarities (of the dc supply, flashtube, and trigger pulse transformer) shown in Figures 6.1-7 and 6.1-8 permit reliable triggering over wide ranges of capacitor charging voltages.

Trigger-pulse classes are a convenient way of relating the parameters of the trigger pulse to the operational requirements of the flashtube. The trigger pulse requirements of flashtubes are generally divided into three classes based on the open-air gap that the trigger energy will jump. These classes are defined below, and the corresponding trigger pulse parameters are listed in Figure 6.1-10.

Class I triggering must jump a 1/8-inch air gap. It is used with low-energy portable photographic flashtubes.

Class II triggering must jump a 3/16-inch air gap. It is used for high-energy studio flashtube lamps, for graphic arts and reprographic applications, and for repetitive flashing.

Class III triggering must jump a ¼-inch air gap. It is used only with some high-energy flashtubes.

6.2 Strobotrons

Strobotrons are cold-cathode gas-discharge lamps of relatively low power ratings which are designed for repetitive flashing at rates in the range of low audio frequencies. Stroboscopes, as the instruments containing strobotrons and their operating circuits are called, are used for measurement of the cyclical rates of motion of rotating and reciprocating machine elements, for inspection of machinery in motion, and for a number of photographic applications.

Strobotrons are generally filled with neon or xenon, although other gases or combinations of gases may be used to produce desired special characteristics. Neon strobotrons generate characteristic red discharges of relatively low intensity, and xenon strobotrons generate characteristic blue-white discharges of higher intensity. When operated under simultaneous conditions of maximum allowable power dissipation and maximum allowable energy input per flash, neon strobotrons have specified maximum flashing rates of 60 to 240 flashes per second, and xenon strobotrons have specified maximum flashing rates of 20 to 100 flashes per second. These specified maximum flashing rates can be exceeded provided that the maximum allowable power dissipation rating and maximum allowable energy input per flash are not exceeded. Under these conditions neon strobotrons can achieve flashing rates up through the audio-frequency range, but xenon strobotrons have an inherently lower limit.

Some strobotrons have external trigger electrodes which require high-voltage pulses for triggering, and some have internal grids which permit triggering by pulses of much lower voltage. Figure 6.2-1 shows a typical strobotron.

The operating circuits of strobotrons are usually capacitor-discharge circuits like those of xenon flash lamps in that they provide high peak currents at low average powers, but unlike those of most xenon flash lamps in that they are designed for repetitive flashing over a relatively wide range of frequencies. These circuits usually can be operated in a free-running mode for measuring cyclical rates of motion, or they can be synchronized to the cyclical rate for stop-motion inspection of moving parts.

When the flashing rate is adjusted to be such that an object with cyclical motion is illuminated only when it is in a specific position in its cycle, that object will appear to stand still, and its motion is said to be 'stopped'. A slightly lower flashing rate than that which 'stops' motion will cause the object to appear to move slowly forward through its cycle, and a slightly higher flashing rate will cause the object to appear to move slowly backward through its cycle. Cyclical motions which actually occur at high speeds can thus be studied in slow motion; i.e., as if they were occuring at much lower speeds.

DESIGN PARAMETER	CLASS I	CLASS II	CLASS III
Peak Voltage, min.	4 KV	10KV	20KV
Initial Rise Time, max.	3 μsec	3 μsec	to design
Frequency, min.	25 kHz	25 kHz	25 kHz
Duration, min. (to 10% output)	50 μsec	100 μsec	to design
Input Energy	3.2 mJ	20 mJ	120 mJ

Figure 6.1-10 Flashtube trigger-pulse requirements.

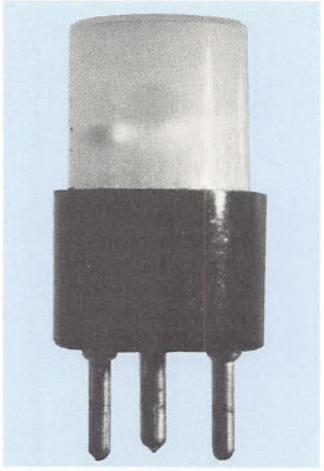


Figure 6.2-1 Typical strobotron.

7.0 Special Purpose Lamps

The lamps described in this section were originally designed for various specialized applications, but are included here because of their potential usefulness in other fields. The present group provides a variety of concentrated sources with diameters in the range from .127 to 2.79mm (.005 to .110in); these can be used effectively as virtual point sources in many optical systems.

7.1 Zirconium-Cathode and Tungsten-Cathode Concentrated-Arc Lamps

These lamps provide extremely small-diameter sources of stable color temperatures and of high luminances which can be modulated at frequencies up to and exceeding 10kHz. Wattages range from 2W to 300W, light-source diameters range from .127 to 2.79mm (.005 to .110in), and luminances range from 1750 to 4500cd/cm² (11,300 to 29,000cd/in²) respectively. Such luminances are several times those of tungsten filaments in conventional incandescent lamps, and are nearly equal to those of carbon arcs. The concentrated-arc lamp is therefore useful in the fields of microscopy, metallography, reprography and quality control, in applications such as optical testing and inspection, lensless projection and enlargement, shadowless lighting, and in entirely new optical systems and instruments requiring narrow-beam, high-intensity light sources.

Zirconium-Cathode Concentrated-Arc Lamps

These lamps contain an argon gas fill, a metallic positive electrode or anode, and a negative electrode or cathode which is coated with zirconium oxide. During operation the argon arc heats the oxide surface of the cathode, a small spot of molten metallic zirconium is liberated from the oxide, and a cloud of vaporized zirconium and zirconium oxide is formed in a region extending a few thousandths of an inch above the molten spot on the cathode. The spot of molten zirconium on the cathode surface and the cloud of zirconium/zirconium-oxide vapor directly over the molten spot produce an intense white light. The cloud of vapor is continuously formed and returned to the cathode, thus renewing the surface of the cathode and resulting in exceptionally long life. Figure 7.1-1 shows a typical zirconium-cathode concentrated-arc lamp.

These lamps are available in both side-view and end-view configurations. Because of the extremely small source diameters, the lamp bulbs are made of unusually clear glass which is free of striae and bubbles that would cause variations of intensity across the projected field. For applications in which such effects must be kept to a minimum, a number of end-view lamps are available with windows made of ground and polished flats of optical glass.

Tungsten-Cathode Concentrated-Arc Lamps

In zirconium-cathode concentrated-arc lamps, a slow lateral shift of the light source may occur during operation; the maximum

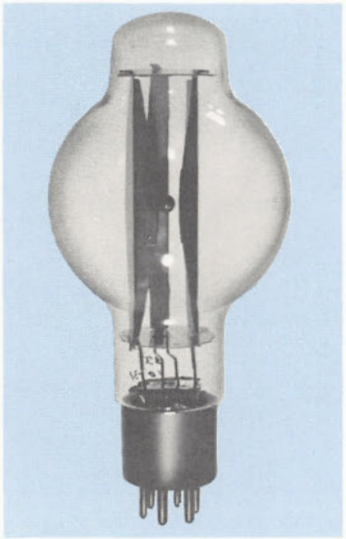


Figure 7.1-1 Typical zirconium-cathode concentrated-arc lamp.

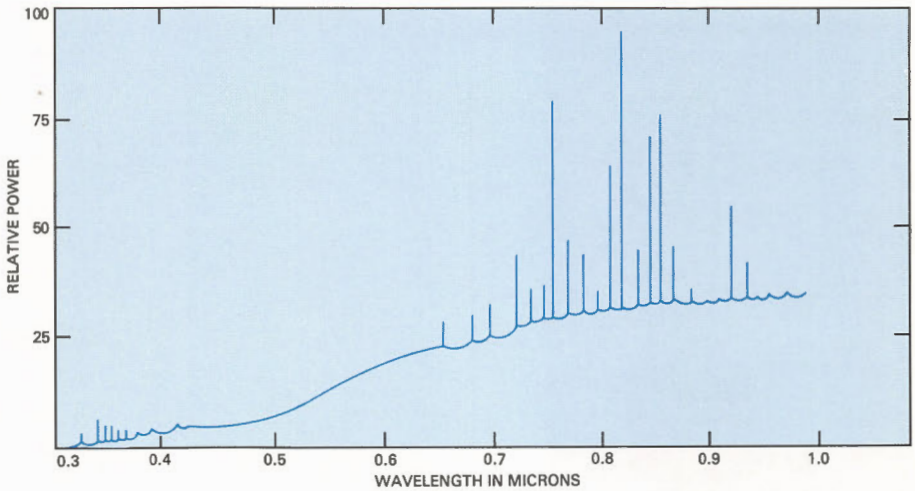


Figure 7.1-2 SPD of typical zirconium-cathode concentrated-arc lamps.

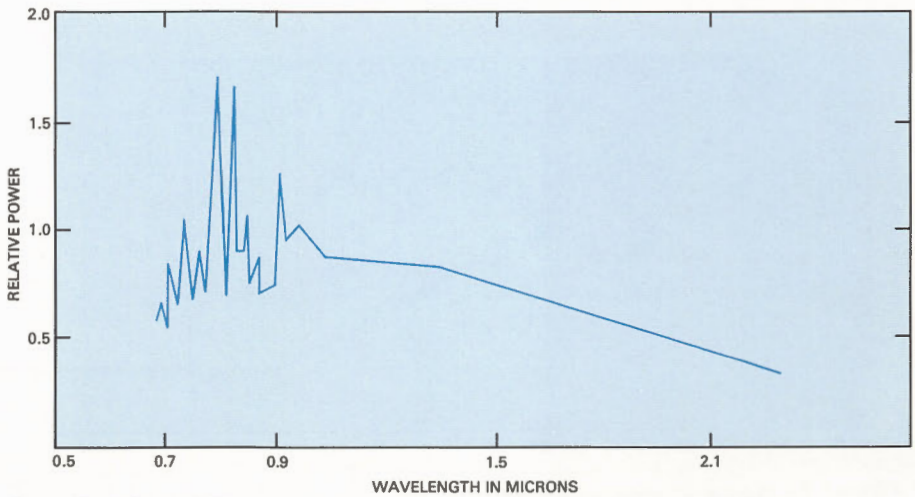


Figure 7.1-3 SPD of 2W tungsten-cathode concentrated-arc lamps.

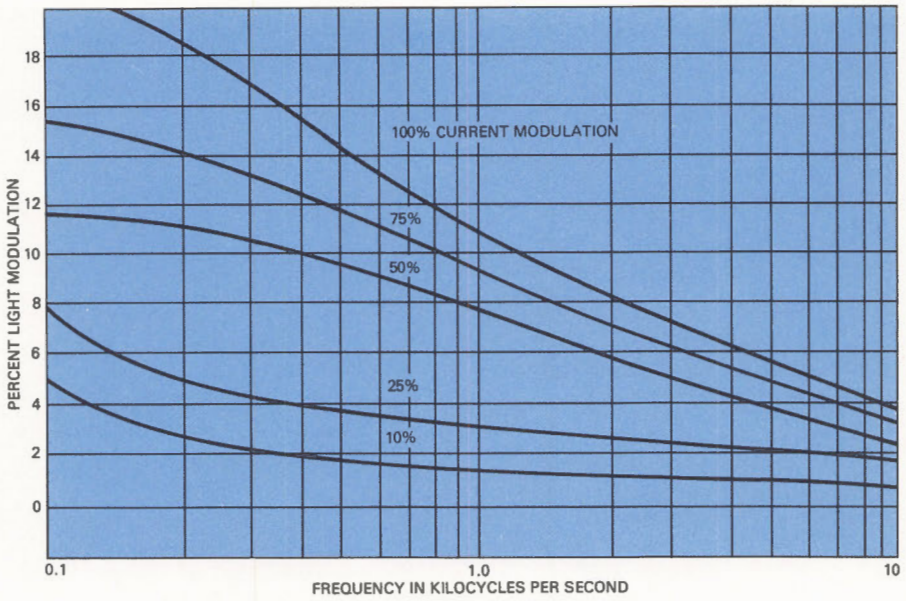


Figure 7.1-4 Modulation characteristics of a 100W zirconium-cathode concentrated-arc lamp.

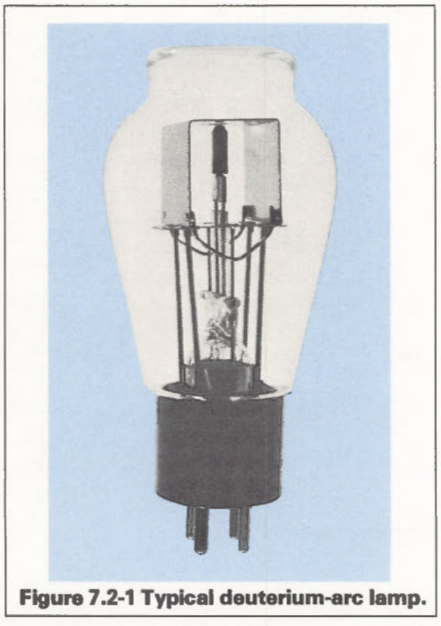


Figure 7.2-1 Typical deuterium-arc lamp.

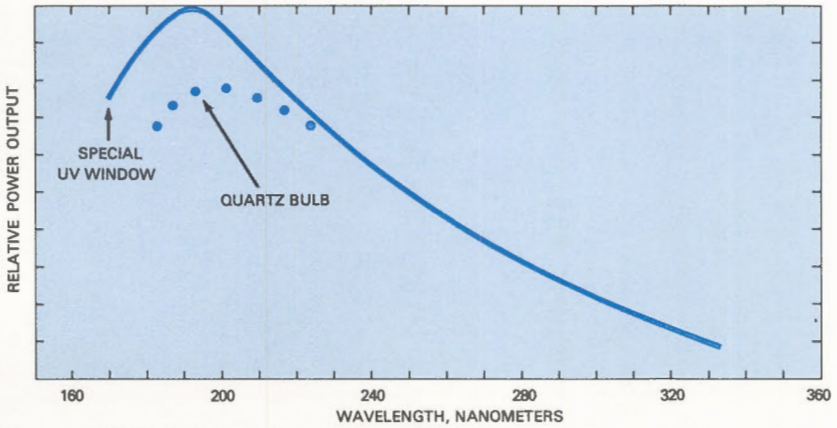


Figure 7.2-2 Typical deuterium-arc lamp SPD.

value of this shift decreases from about one half the source diameter in the 2W and 10W sizes to about one-quarter the source diameter in the 300W sizes. This shift is usually unimportant, but for applications requiring extreme lateral stability, some 2W end-view lamps are available with cathode surfaces of tungsten instead of zirconium oxide. These tungsten-cathode lamps have lower luminances (1750 cd/cm², or 11,300 cd/in²) than the luminances (2400 cd/cm² or 15,500 cd/in²) of the zirconium-cathode lamps.

Light source diameters range from .127 to 2.79 mm (.005 to .110 in).

Average Luminances range from 1750 to 4500 cd/cm² (11,300 to 29,000 cd/in²).

Color temperature is about 3200K.

Spectral power distribution of typical zirconium-cathode lamps is shown in Figure 7.1-2, and the SPD of the 2W tungsten-cathode lamps is shown in Figure 7.1-3.

Spatial distribution. Since the light originates from a point on the cathode surface, it is emitted in one hemisphere only, and the intensity varies as the cosine of the angle with respect to the normal from the cathode surface.

Modulation characteristics vary significantly with ratings. The modulation characteristics of a 100W zirconium-cathode concentrated-arc lamp are shown in Figure 7.1-4.

Operating Characteristics

Except for the 300W lamp which will operate on either ac or dc, all of these concentrated-arc lamps operate on dc only, and when the main supply is ac, they require special rectifier power supplies that can provide momentary starting voltages of 1000V or 2000V, lamp operating voltages in the range of 16V to 38V, and sufficient equivalent series ballast impedance to limit operating currents to rated values.

Minimum starting voltages are 1000V (2, 10, and 25W lamps) or 2000V (100 and 300W lamps).

Minimum supply voltages are 40V (300W lamps); 50V (10, 25 and 100W lamps) or 200V (2W lamps).

Lamp operating voltages range from 16V (100W lamps) to 38V (2W lamps).

Rated life ranges from 150 hrs. (2W lamps) to 450 hrs. (10W lamps).

7.2 Deuterium-Arc Lamps

Deuterium-arc lamps are highly efficient, compact lamps which provide very small (1.2mm diameter) sources of intense ultraviolet radiation. Their present major applications are in ultraviolet spectrophotometry for analyses of organic and inorganic materials, and in specialized studies of fluorescence, phosphorescence, and UV reflectance. Figure 7.2-1 shows a typical deuterium-arc lamp.

The envelopes of these lamps are made from clear fused silica for high ultraviolet transmission and for resistance to both thermal and physical shock. The DE450 has a five-pin medium base; most of the other lamps have five-inch insulated leads with terminal connectors.

Illumination Characteristics

Source diameters are 1mm or 2mm. Types DE550, DE650/B/C/D, and DE750 have 1mm diameter sources. Types DE50A, DE250A, DE450/A have 2mm diameter sources.

Spectral power distributions of typical deuterium-arc lamps are shown in Figure 7.2-2. Note that types DE50A, DE550, DE650/B and DE750 have standard fused-silica ('quartz') bulbs that transmit from 200-380nm, while types DE250A, DE450, and DE650C/D have special UV windows that transmit from 185-380nm.

Operating Characteristics

Lamps with 1mm source diameters (DE550, DE650/B/C/D, and DE750) are rated for 300 mAdc operating current, ac or dc starting voltages of 250 or 350V, and dc anode operating voltages in the range of 65-95V. Some require ac or dc filament power during both start-up and operation, and some require filament power for start-up only.

Lamps with 2mm source diameters (DE50A, DE250A, DE450/A) are rated for 800mAdc operating current, ac or dc starting voltages of 100V, and dc anode operating voltages of 40V. They require ac or dc filament power of 4V at 15A only until start-up.

Rated life of lamps with 1mm source diameters is 500 hours and with 2mm source diameters is 200 hours at maximum rated currents.

7.3 Glow-Modulator Tubes

Glow-modulator tubes are cold-cathode concentrated light sources with high-intensity outputs that can be modulated at frequencies from dc to more than 1,000,000Hz. The cathode is a small hollow cylinder at the output end of which a small arc crater produces a concentrated discharge of high ionization density. Although glow-modulator tubes were originally developed to meet the specialized requirements of facsimile receivers, their intense actinic light output, approximate linear relationship between light output and tube current input, and high-frequency modulation capabilities are useful for other applications in industry, science, and communications. Figure 7.3-1 shows a typical glow-modulator tube.

Illumination Characteristics

Spectral power distributions. Glow-modulator tubes fall into two groups, those with white outputs and those with blue-red outputs. Figure 7.3-2 shows the SPD of glow-modulators with white outputs, and Figure 7.3-3 shows the SPD of glow-modulators with blue-red outputs.

Crater diameters range from .38 to 2.36mm (.015 to .093in).

Light outputs range from .023 to .2 cp at rated currents.

Luminances range from 2.3 to 20.5cd/cm² (15 to 132cd/in²) at rated currents.

Input-output characteristics of typical glow-modulator tubes are shown in Figure 7.3-4, which is a static characteristic showing relative light output versus tube current.

Frequency response of typical glow-modulator tubes is shown in Figure 7.3-5 which is a plot of relative light output versus the modulating frequency. Note that the relative light output falls only about 30% (3db) at a modulating frequency of 1 MHz.

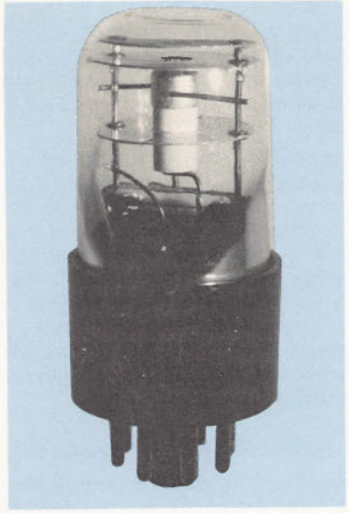


Figure 7.3-1. Typical glow-modulator tube.

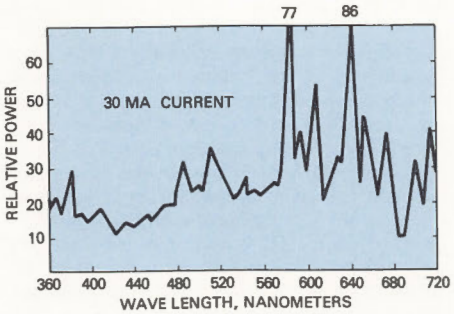


Figure 7.3-2 SPD of typical glow-modulator with white output.

Operating Characteristics

Minimum starting voltages are 225 or 240V.

Maximum operating voltages are 150 or 160V.

Operating currents have maximum allowable averages in the range of 15-35mA, and peak allowable values in the range of 30-75mA.

Rated life ranges from 25-250 hrs. at stated currents.

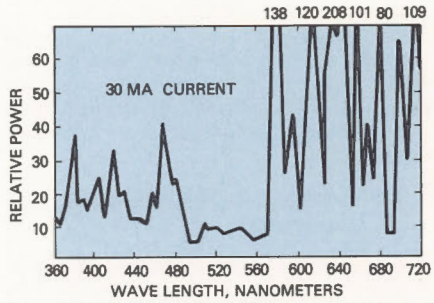


Figure 7.3-3 SPD of typical glow-modulator with blue-red output.

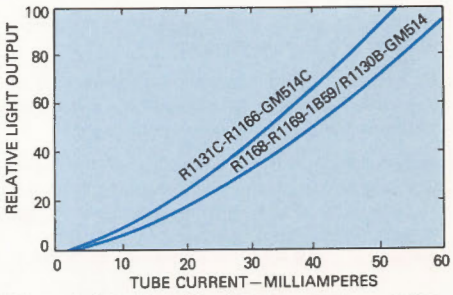


Figure 7.3-4. Relative light output vs. tube current for typical glow-modulators.

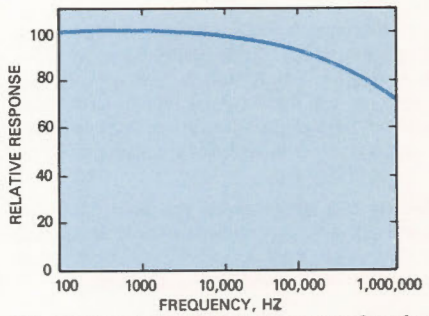


Figure 7.3-5. Frequency response of typical glow-modulators.

8.0 Optical Coatings

Thin films of dielectric, semiconductor, or metallic materials may be applied to optical components (e.g., the faceplates and/or bowls of PAR lamps) to alter their spectral and/or total reflectance and transmittances. Such thin-film coatings, consisting of only one layer or as many as fifty or one hundred layers, may be used to suppress undesired reflections, to enhance desired reflections, to transmit desired wavelengths, and/or to reflect desired wavelengths. The coatings of more than one layer employ the phenomenon of optical interference and are therefore called multilayer interference filters.

8.1 Principles of Optical Coatings

The principle of superposition states that the resultant amplitude of any number of light waves at any point is equal to the algebraic sum of the amplitudes of the individual waves at that point. If all the light waves at a given point are sinusoidal electromagnetic waves of a given frequency, then the resultant of those light waves at that point will be a sinusoidal electromagnetic wave of the given frequency.

Coherence exists between two light waves of the same frequency when the phase difference between the two light waves is constant.

Interference is the modification of the resultant amplitude at any point resulting from the superposition of two or more mutually-coherent beams of light. Constructive interference causes the resultant amplitude to be greater than the individual amplitudes, and destructive interference causes the resultant amplitude to be less than the individual amplitudes. Interference is illustrated in Figure 8.1-1 by the resultant 3 of the superposition of two coherent waves 1 and 2. Figure 8.1-1(a) shows constructive interference when the two waves are in phase. Figure 8.1-1(b) shows partial destructive interference when two waves of unequal amplitude are 180° out of phase, and Figure 8.1-1(c) shows complete destructive interference when two waves of equal amplitude are 180° out of phase.

Energy of a light wave at any point is proportional to the square of the amplitude of the wave at that point, and is accordingly modified by constructive and destructive interference.

Interference in thin films may result from the combination of two effects: a difference in optical path lengths of light rays reflected from the first and second surfaces of those films, and phase reversals in the reflected rays that may occur at either or both surfaces. Whenever a light ray travelling in one transmission medium meets the surface of a second medium, part of the ray is usually reflected at the boundary and part is refracted into the second medium. If the refractive index of the second medium is higher than that of the first, the phase of the reflected ray will be changed by one-half wavelength, and thus will be reversed. If the refractive index of the second medium is lower than that of the first, the phase of the reflected ray will not be reversed.

Figure 8.1-2 shows a thin film of thickness t on the surface of a glass substrate. At a given wavelength, the film has the refractive index n_2 and optical thickness n_2t and the glass has the refractive index n_3. A ray of light of wavelength λ strikes the film at the angle of incidence ϕ_1. Part of the ray is reflected with a phase reversal because the index n_2 of the film is greater than that of air (for which $n = 1$), and part of the ray is refracted into the film at the angle ϕ_2. This refracted ray is reflected at the film-glass interface, with reversed phase if $n_2 < n_3$ and without reversed phase if $n_2 > n_3$. The ray is then refracted out of the film into the air, parallel to the ray reflected at the air-film interface. The optical path difference between the two rays can be shown to be $2n_2t \cos \phi_2$. If the two rays are in phase, constructive interference will occur and reflection will be increased; conversely, if the two rays are 180° out of phase, destructive interference will occur, and reflection will be decreased.

In general, if $n_2 > n_3$, the reflected rays will constructively interfere (thus enhancing reflection) at wavelengths for which the film optical thickness n_2t is an odd multiple of one-quarter wavelength. The reflected rays will destructively interfere (thus reducing reflection) when n_2t is an even multiple of one-quarter wavelength. The converse effects occur when $n_2 < n_3$. Thus, by using thin films of suitable thickness and refractive index, reflection can be enhanced or reduced at any desired wavelength.

8.2 Antireflection Coatings

Whenever light passes through a transmission medium having an index of refraction n_1 into a transmission medium having a different index of refraction n_2, some light may be reflected at the interface between the two media. Such reflections occur when light passes from air ($n = 1.0$) into glass ($n = 1.4$ to 1.9) or from glass into air. The reflectance approaches 100% as the angle of incidence approaches 90% (i.e., 'grazing incidence', when the incident ray is nearly parallel to the interface), and decreases to a minimum at 0° angle of incidence (i.e., 'normal' incidence, when the light is at 90° to the interface). Reflectance between these two limits is a function of the polarization state of the incident light, as well as of the characteristics of the media. The value of the minimum reflectance R_0 (the subscript represents 0° angle of incidence) for any interface between media of indices n_1 and n_2 is

$$R_0 = \left[\frac{n_1 - n_2}{n_1 + n_2}\right]^2 \qquad \text{(eq. 8.2-1)}$$

If n_1 = the index of glass, and n_2 = the index of air, the equation becomes

$$R_0 = \left[\frac{n_1 - 1}{n_1 + 1}\right]^2 \qquad \text{(eq. 8.2-2)}$$

Most glasses have refractive indices between 1.5 and 1.9, for which the corresponding minimum reflectances per surface are calculated from the above equation to be 4% and 9.6% respectively.

Figure 8.2-1(a) shows the minimum reflection losses occurring at the air-glass and glass-air interfaces of a glass plate having a refractive index of 1.5. Assuming 100 units of light entering the first surface, 4 units will be reflected and 96 units will enter the glass. At the second surface, 3.8 units will be reflected and 92.2 units will be transmitted through the glass. The total reflection loss will be 4 + 3.8 or 7.8 units. (In this simplified explanation other effects, such as multiple reflections between the two surfaces, have been neglected.)

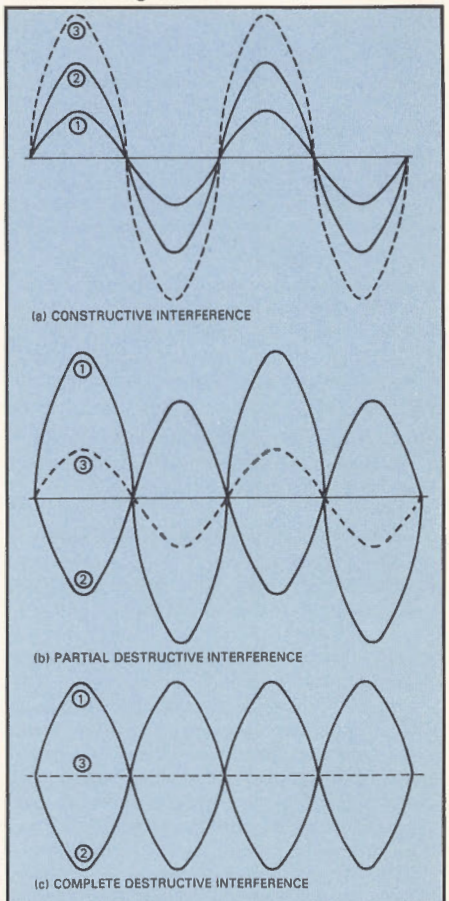


Figure 8.1-1 Constructive and destructive interference.

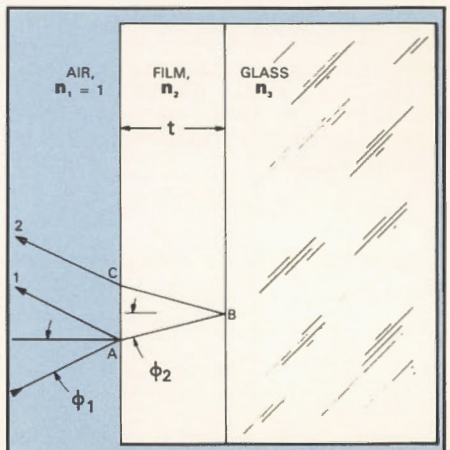


Figure 8.1-2 Interference effects in thin films.

Figure 8.2-1(b) shows the minimum reflection losses in a glass plate having a refractive index of 1.9. Of 100 units of light entering the first surface, 9.6 and 8.7 units will be reflected at the first and second surfaces respectively, and only 81.7 units will be transmitted through the glass. The total reflection loss will be 9.6 + 8.7 = 18.3 units.

In the examples above it must be remembered that the total reflection losses of 7.8% and 18.3% for the two glasses are the minimum reflection losses, occuring at 0° angle of incidence, and that reflection losses increase from these minima as the angles of incidence increase. In optical systems containing several interfaces at which reflections can occur, the reflection losses will not only reduce the brightness of the desired beam or image, but the reflected light will be dispersed throughout the system by subsequent reflections, causing reduced contrast, and sometimes even the phenomenon called flare.

The problems caused by reflections at the surfaces of glass optical components can be effectively minimized by coating the surface with one or more 'tuned' layers of index-matching materials, which increase effective transmittance by reducing reflectance. For example, if the optical thickness n_2t of the thin film in Figure 8.1-2 is one-quarter wavelength at any desired wavelength, and the index of refraction of the film is equal to the square root of the index of the glass (**i.e.**, $n_2 = \sqrt{n_3}$), then there will be no reflections at the first surface. If the second surface of the glass is coated in the same way, there will be no reflections at that surface either. This is shown in Figure 8.2-1(d), where a glass plate with **n** = 1.9 is coated on both faces with quarter-wave layers of magnesium fluoride (**n** = $1.38 = \sqrt{1.9}$). Reflections at both surfaces are completely eliminated, so that if there is no absorption in the glass, nearly 100% transmittance will occur. Note that this ideal effect will only occur in the case of true index-matching and is somewhat reduced when the index of the glass is less than 1.9, as in Figure 8.2-1(c). The spectral reflectance of uncoated crown glass (**n** = 1.5) and the reductions that can be achieved by single-layer magnesium flouride AR coating, as well as by two types of multilayer AR coatings, are shown in Figure 8.2-2.

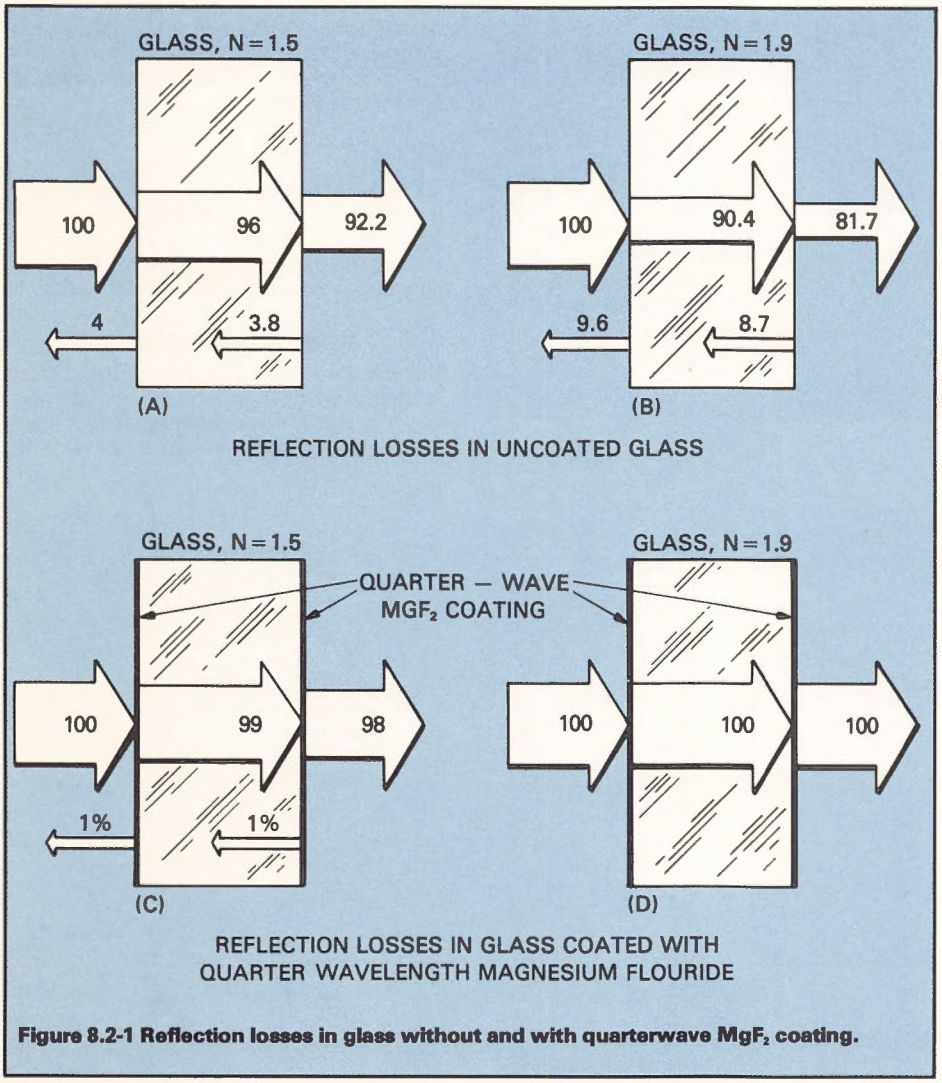


Figure 8.2-1 Reflection losses in glass without and with quarterwave MgF_2 coating.

Types of Antireflection (AR) Coatings

Magnesium fluoride AR coatings are extremely hard and durable single-layer coatings. For most visual applications, the coating is 'peaked' for minimum reflectance at 550nm, but it can be peaked at other wavelengths. Reflection losses per surface are about 1.25% for glass with **n** = 1.5 and about 1.8% for fused silica, and remain below 2% from 400 to 700nm for both materials.

Broadband AR coatings are hard and durable multilayer dielectric coatings that reduce reflection losses per surface to an average of 0.5% across the visible. The maximum loss at any wavelength between 400 and 700nm is less than 1.25%.

Low-Loss AR coatings, sometimes called 'V' coatings, are sharply-tuned multilayer dielectric coatings that reduce reflection losses per surface to less than 0.25% over a narrow band (e.g., ±20nm) about a specified peak wavelength.

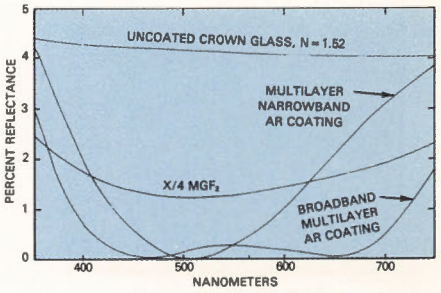


Figure 8.2-2 Reflectance of typical crown glass, uncoated, and with various antireflection coatings.

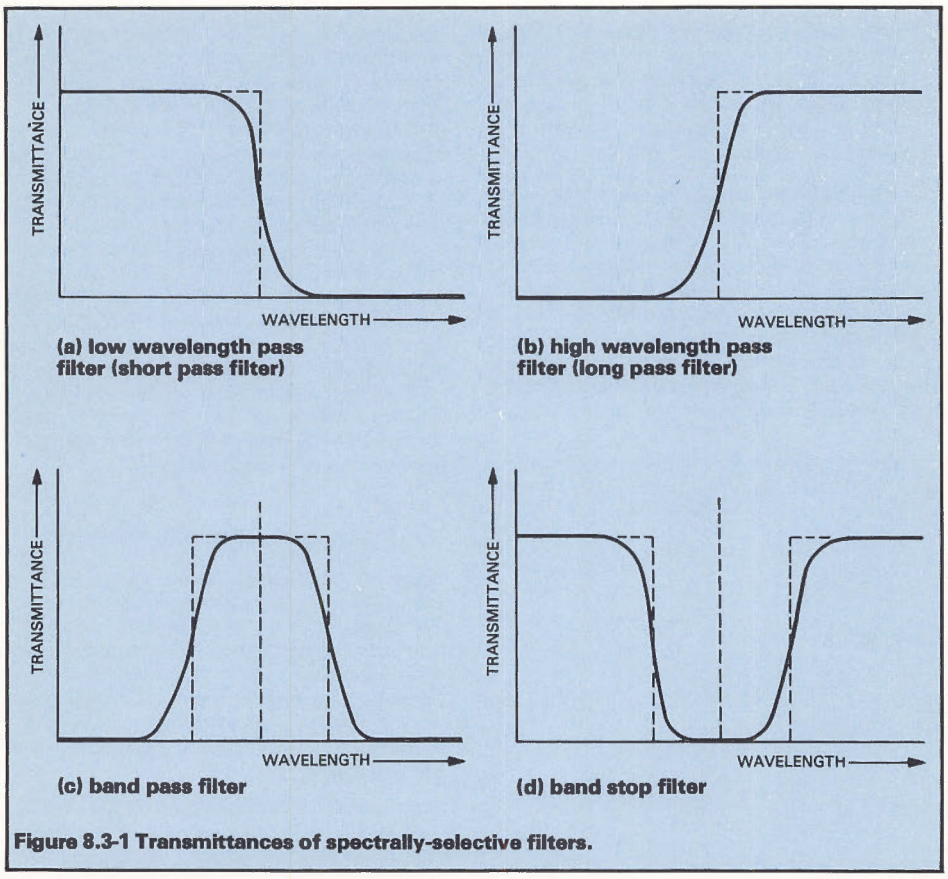

TRANSMITTANCE
WAVELENGTH
(a) low wavelength pass filter (short pass filter)
(b) high wavelength pass filter (long pass filter)
(c) band pass filter
(d) band stop filter

Figure 8.3-1 Transmittances of spectrally-selective filters.

8.3 Spectrally Selective Filter Coatings

As shown in Figure 8.3-1, multilayer filters can be designed to pass wavelengths below or above certain wavelengths, or to pass or reject bands of wavelengths. The steepness of all the filters, and the percent bandwidth of the bandpass and bandstop filters, can be controlled by varying the number of layers. These filters are usually designed for normal incidence, and tilting them shifts the passband towards shorter wavelengths. Sometimes this effect is used for 'tuning' a filter slightly. The generalized curves of Figure 8.3-1 can be applied to filters for use at ultraviolet, visible, and near-infrared wavelengths.

Various types of spectrally-selective filters can be applied to lamp bulbs to select desired wavelengths as in Figure 8.3-2, by coating the faceplates. These coatings are more efficient than color-absorbing filters, and the resulting colors are more brilliant.

Filters

Filters can also be used to correct color temperatures. For example, PAR36 studio lamps, which have an inherent color temperature of about 3350K, can be corrected to color temperatures in the range of 5000K to 6000K.

8.4 Dichroic Mirrors

Figure 8.4-1, the spectral power distribution of a typical incandescent lamp, shows that most of the output is in the infrared which causes heating of surfaces it irradiates. When such

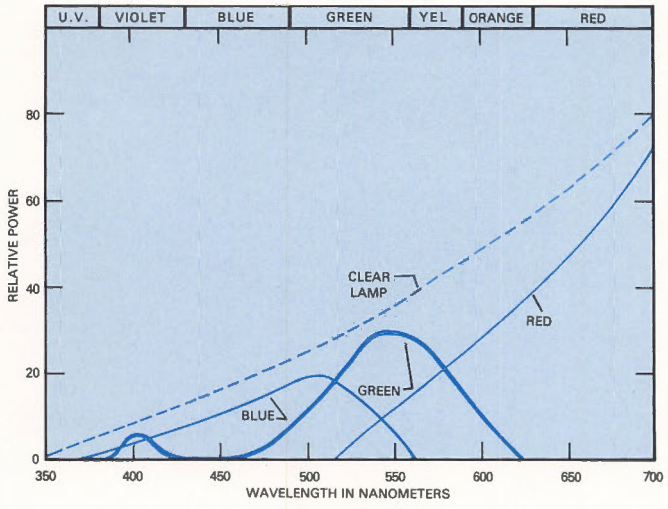


Figure 8.3-2 Spectral power distributions of PAR lamps with clear and filter-coated faceplates.

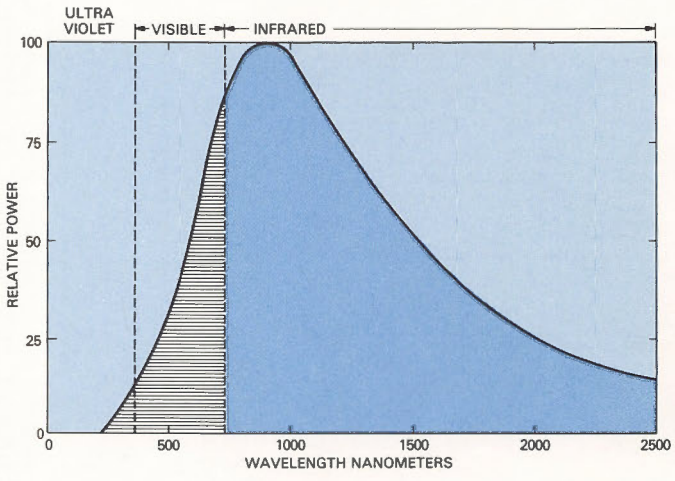


Figure 8.4-1 Spectral power distribution of typical 3000K tungsten lamp.

lamps are used for projection, it is desirable to transmit the visible radiation and to block the infrared.

Wavelength-selective beam-splitters, called dichroic mirrors, can be used for this purpose. There are two kinds of dichroic mirrors, the 'hot'mirror and the 'cold' mirror. Hot mirrors reflect infrared radiation and transmit the visible, while cold mirrors transmit infrared and reflect the visible. Figures 8.4-2 and 8.4-3 show spectral characteristics of ideal and actual dichroic mirrors, respectively. PAR lamps are available with cold-mirror reflectorized bowls that permit high illumination levels on food and merchandise with greatly reduced heating effects. These PAR lamps have 75 to 80% of the heat removed from the beam at a loss of only 10% or less of the light output.

Figure 8.4-4 shows some projection-type uses of hot and cold mirrors. Note that the angle of incidence for the ellipsoidal cold mirror is in the range of 45°, and that of the plane hot mirror approaches 0° (normal incidence).

8.5 Metallic Mirrors

The most common coating for optical mirrors is aluminum, the reflectance of which is near 90% from 200nm in the ultraviolet through the visible. After a small dip near 850nm, the reflectance rises to about 97% in the infrared. The aluminum is usually protected with a half-wavelength thickness of silicon monoxide, but silica and magnesium fluoride are also used. By proper design of these coatings, the reflectance can be enhanced to almost 100% over a fairly wide range of wavelengths.

Solid aluminum surfaces used as reflectors are usually protected by an anodic coating of aluminum oxide producing an effective reflectance of about 85% in the visible. This can be enhanced to about 94% by means of thin film coatings.

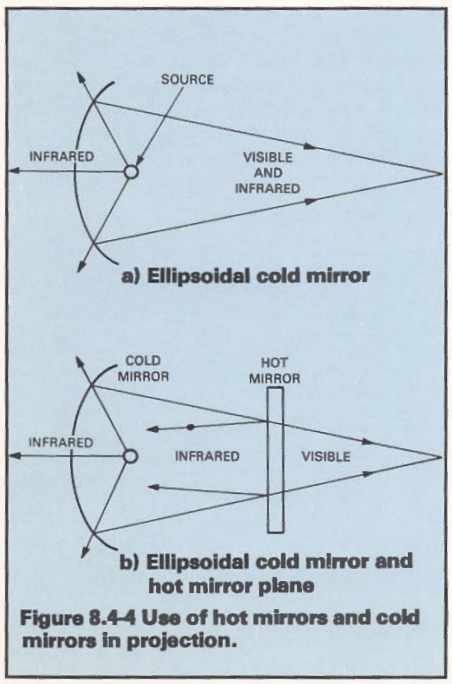


Figure 8.4-4 Use of hot mirrors and cold mirrors in projection.

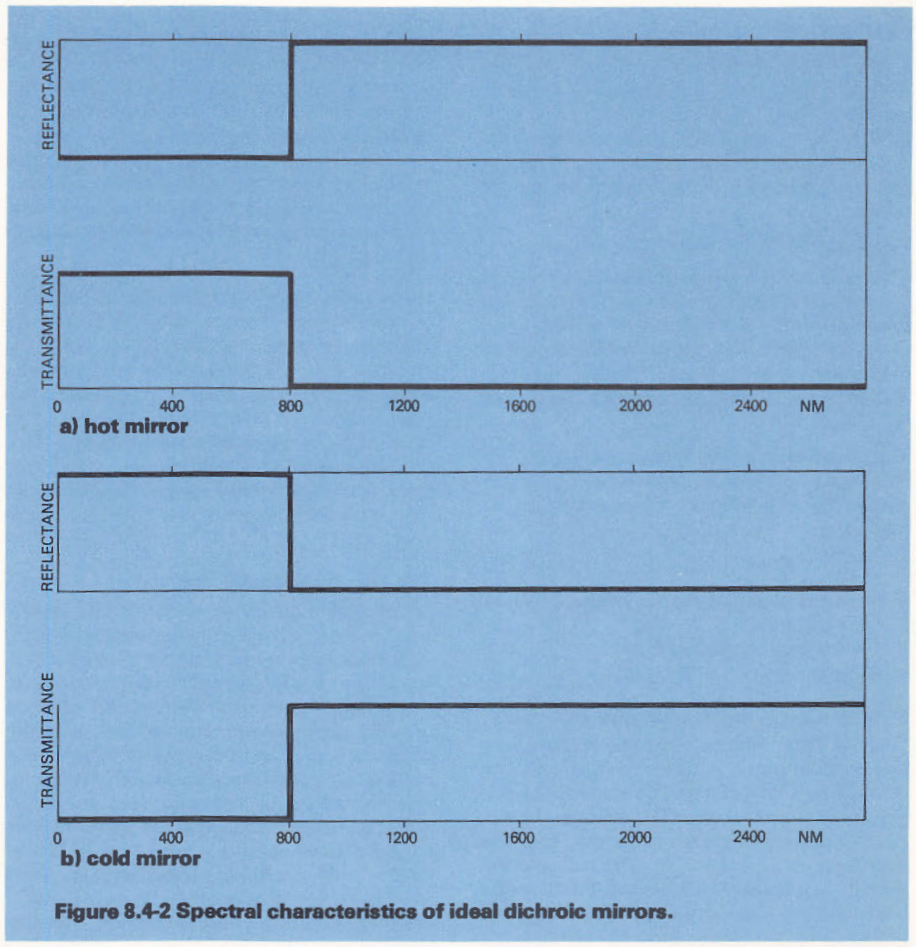


Figure 8.4-2 Spectral characteristics of ideal dichroic mirrors.

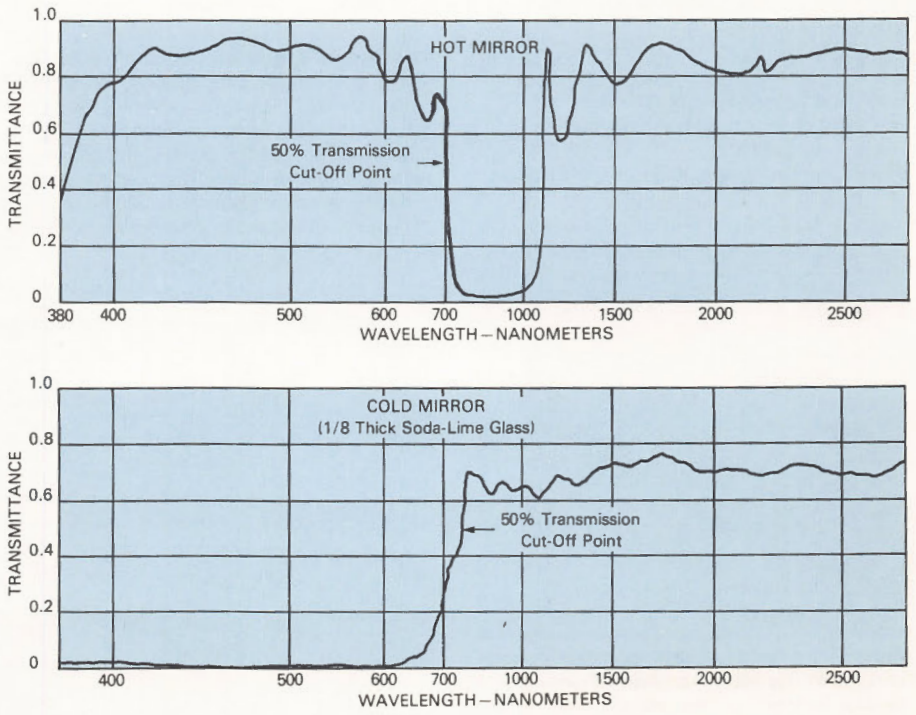


Figure 8.4-3 Spectral characteristics of typical actual dichroic mirrors.

9.1 Electromagnetic Radiation

Electromagnetic radiation or radiant energy is energy which does not require a material medium of propagation but which can be radiated through a vacuum as well as through transmissive materials. Electromagnetic radiation has the properties of both particles and of waves.

Propagation in Vacuum

The velocity of propagation or 'speed of light', **c**, of electromagnetic radiation in vacuum is approximately 300 million meters per second (3×10^8 m/sec). This fundamental constant of nature applies to all electromagnetic radiation and not only to that perceived by the eye as light.

The wavelength and frequency of electromagnetic radiation in vacuum are inversely related by the velocity of propagation as follows:

$$\mathbf{c} = \lambda\nu \quad \text{, where} \qquad \text{(eq. 9.1-1)}$$

c = velocity of propagation in vacuum, 3×10^8 m/sec
λ = wavelength in vacuum, m
ν = frequency, Hz (cycles/sec)

Propagation in Material Media

When electromagnetic radiation passes from one medium into a different medium, the frequency does not change, but the velocity and wavelength are changed. The velocity of propagation of radiant energy in material media is always less than in vacuum. These changes in velocity at interfaces between different media cause the phenomenon of **refraction.**

Index of refraction, n, of a transmissive medium is a dimensionless number equal to the ratio of the velocity of propagation in vacuum to that in the medium:

$$\mathbf{n} = \mathbf{c}/\mathbf{v} \quad \text{, where} \qquad \text{(eq. 9.1-2)}$$

n = index of refraction of the medium
c = velocity of propagation in vacuum, 3×10^8 m/sec
v = velocity of propagation in the medium, m/sec

Since the velocity of propagation in vacuum is **c**, the refractive index of vacuum is unity; and since the velocity of propagation in all transmissive material media is less than **c**, the refractive indices of material media are greater than unity. However, the velocity of propagation in air (and in many other gases) is so close to **c** that the refractive index of air (1.00029) may be taken as unity with an error of less than one part in one thousand. Figure 9.1-1 lists the refractive index of various materials at a commonly-used standard wavelength, the 589nm sodium D line. Note that most glasses have refractve indexes in the range 1.4 to 1.6.

MEDIUM	INDEX OF REFRACTION
VACUUM	1.0
AIR	1.000229
WATER	1.333
FUSED SILICA	1.458
BOROSILICATE GLASS	1.481
ACRYLIC	1.492
SODA–LIME GLASS	1.513
ALUMINOSILICATE GLASS	1.525
LEAD–ALKALI GLASS	1.535
POLYCARBONATE	1.586
POLYSTYRENE	1.591

Figure 9:1-1 Index of refraction for various media, at the 589nm sodium D line. Exact values depend on the composition of the material, temperature, pressure, etc.

Dispersion. Velocity of propagation and index of refraction are not only different in different media, but they usually vary with wavelength in any one medium causing the phenomenon known as dispersion. Newton made use of this phenomenon in a glass prism to disperse 'white light' (e.g., sunlight or daylight) into a continuous spectrum of colors ranging from red through orange, yellow, green, cyan, blue, indigo, and violet. This range is called the visible spectrum.

The Electromagnetic Spectrum

The visible spectrum is only an extremely small portion of the electromagnetic spectrum. Figure 9.1-2 represents this spectrum which extends from cosmic rays through gamma rays, x-rays, the ultraviolet, visible and infrared regions, microwaves and radio frequencies, to power-transmission frequencies. Both frequency and wavelength are shown in the figure. Power-transmission and radio waves are usually designated by frequency; microwaves may be designated either by frequency or wavelength; and the infrared, visible, and ultraviolet regions are usually designated by wavelength. The preferred unit of wavelength in those regions is the nanometer (1nm = 10^{-9}m). The Ångström (1 Å = 10^{-10}m) and the micron or micrometer (1 μ = 10^{-6}m) are deprecated units.

The optical spectrum, which includes ultraviolet, the visible, and infrared, is so called because radiant energy in that region of the electromagnetic spectrum generally can be treated by application of the optical laws of reflection and refraction. The optical spectrum, the spectral range from about 200nm to about 2500nm, covers most photographic, reprographic, and micrographic applications.

The visible spectrum is merely that portion of the optical spectrum in which the human eye detects or 'sees' radiation as light and is in no other way different from the other regions of the optical spectrum. As shown in Figure 9.1-2, the visible spectrum covers the range from violet at about 400nm, through blue, green, yellow and orange, to red at about 700nm. There is no absolute cutoff for the visible spectrum; many observers can see over the wider range at high power levels.

Electromagnetic Waves and Particles

Maxwell's electromagnetic wave theory (1864), which postulated that oscilating electric charges produce transversely oscillating electric and magnetic fields that radiate outward in space, permits relatively simple explanations of the phenomena of reflection, refraction, dispersion, interference, and polarization. However, there are a number of phenomena, such as blackbody radiation and the photoelectric effect, that cannot be explained on the basis of wave theory but only by treating radiation as particles (called photons) or as discrete packets of energy (called quanta).

Planck (1900) hypothesized that oscillating electric charges do not emit electromagnetic energy continuously but only in integral multiples of a minimum permissible energy unit (later called the quantum) which is proportional to the frequency of the radiation:

$$\mathbf{E} = \mathbf{h}\nu \quad \text{, where} \qquad \text{(eq. 9.1-3)}$$

E = photon energy
h = Planck's constant, 6.6262×10^{-34} joule•sec
ν = frequency of radiation, Hz

Einstein (1905) suggested that Planck's energy quanta exist in the form of localized bundles or discrete particles (later called photons). Planck's quantum principle as amended by Einstein states that radiation of frequency ν is always emitted or absorbed in a discrete quantity or quantum of energy, $\mathbf{h}\nu$. Einstein was thus able to explain various phenomena produced when electromagnetic energy interacts with matter such as the photoelectric and photochemical effects that had been inexplicable by means of wave theory.

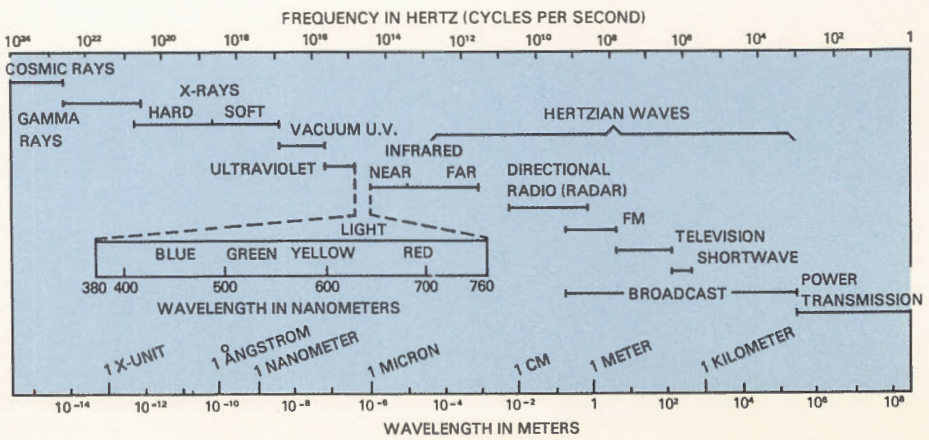


Figure 9.1-2 The electromagnetic spectrum.

Emission of Optical Radiation

Optical radiation including light is energy released by and during the reversion of excited electrons from higher (less stable) to lower (more stable) energy states. Such electronic transitions occur in a number of physical and chemical phenomena. These are usually separated into two major types depending on the means by which the electrons are excited into the higher energy states. When they produce visible radiation, the two types of phenomena are called incandescence and luminescence.

Incandescence

Materials at temperatures above zero kelvins emit broad continuous spectra of electromagnetic radiation. At temperatures below about 600°C (873K), the emitted radiation is mostly infrared; but at higher temperatures, materials emit light in addition to the infrared, i.e., they become incandescent. Conventional tungsten-filament lamps and tungsten-halogen lamps generate light from the incandescence of tungsten filaments heated by electric currents. Flashbulbs generate light from the incandescence of certain metals (e.g., zirconium or hafnium) which are burned rapidly in an oxygen atmosphere. Regardless of the means employed to achieve incandescence, the mechanism of the process is as described below.

Incandescence, which is caused by thermal excitation of an ensemble of electrons, atoms, and molecules, is the emission of a broad continuous spectrum of radiation which includes not only the visible, but usually also contains a large component of the so-called 'free-free' transitions of electrons which contribute especially strongly in the infrared. Since in thermal excitation all components share equally ('equipartition of energy'), transitions of all possible wavelengths are excited and the spectrum of emitted radiation is very broad, extending from the far infrared to the ultraviolet. The 'free-free' transitions mentioned above result from the deflections of free electrons passing in close proximity to positively-charged atomic nuclei. Such deflections constitute acceleration of those electrons which therefore radiate energy because, according to electromagnetic theory, all accelerated charges must radiate. The photon energy radiated by the free-free transition of an electron is, according to quantum theory, equal to the difference in energy between the two free states of the electron.

Free electron states exist in a continuous ladder, the steps of which are separated by small energy increments. Since the separation between states is very small, the spectrum of the radiation which results from such free-free transitions is essentially continuous, as distinguished from the discrete lines which result from the transitions of electrons from one bound state to another. Therefore it usually extends across a very broad band of wavelengths and extends into the far infrared.

Luminescence

In luminescence the means of excitation, e.g., ultraviolet radiation, x-radiation, electron bombardment, etc., is usually much more selective than thermal excitation and excites only a limited number of optical transitions. Thus, the emitted radiation is confined to a few selected bands or spectral lines and, in particular, does not usually extend far into the infrared region. Luminescent light sources are usually categorized in terms of the means of excitation which causes the generation of light as follows:

Gaseous discharges emit radiation at spectral lines characteristic of the gases employed when those gases are excited by the passage of electrical currents through them.

Fluorescence is the emission of light as the result of, and only during, the absorption of radiation. The wavelength of the emitted light is usually, though not always, equal to or greater than the wavelength of the absorbed radiation. The excitation of the phosphor by the gas discharge in a flourescent lamp is an example of fluorescence.

Phosphorescence is the emission of light as the result of the absorption of radiation and continuing for a noticeable length of time after termination of excitation. The afterglow of the phosphor in a fluorescent lamp is an example of phosphorescence.

Other types of luminescence include electro-, cathodo-, galvano-, crystallo-, chemi-, thermo-, tribo-, sono-, radio-, and ionoluminescence, as well as the light-generating processes in light-emitting diodes (LEDs) and lasers.

Combined Incandescence and Luminescence

Arcs usually produce optical radiation by a combination of thermal emission and gaseous discharge. They emit combined line and band spectra from excited gases or vapors, and continuous spectra from the incandescent electrodes as well as from free-free transitions by free electrons in the gases when large currents are passed through the arcs by means of the electrodes.

Laws of Thermal Emission of Radiation

All matter is made up of molecules which are in their lowest energy states at absolute zero temperature (0 kelvins, -273.15°C), but which at all temperatures above absolute zero are in constant oscillatory motion owing to thermal agitation; the velocity, and kinetic energy of course, increase with temperature. Not all the molecules are excited to the same extent; when the number of molecules at each energy is plotted against energy, a skewed distribution curve results over a wide range of energies.

As Maxwell showed, oscillating electrical charges radiate electromagnetic energy. Since the atoms and molecules of matter contain electrical charges, thermal agitation of those molecules will cause them to oscillate and thus to radiate electromagnetic energy. The distribution of this energy with frequency is related to the distribution of numbers of thermally-agitated molecules, so that electromagnetic radiation is emitted over a wide range of frequencies and wavelengths. Also in accordance with the distribution of molecular agitation in an object, as the temperature of the object is increased, the total radiated energy increases, and the peak shifts to higher frequencies (shorter wavelengths). The laws describing the various phenomena of thermal emission of radiation are briefly described below.

Lambert's cosine law (1760) states that the radiant intensity from an ideal diffuse radiator is proportional to the cosine of the angle from the normal to its surface. Surfaces obeying this law will have constant radiance in all directions, i.e., they will appear equally bright from any angle.

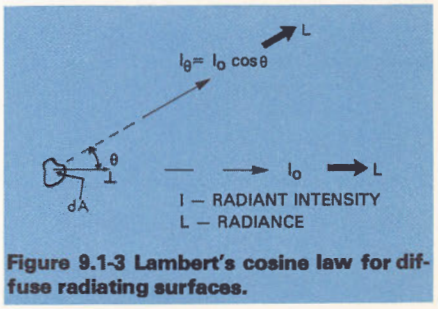


Figure 9.1-3 Lambert's cosine law for diffuse radiating surfaces.

Kirchoff's principle of radiation (1859) states that the emittance ϵ of any surface is equal to its absorptance, α. Thus highly absorptive surfaces are good thermal emitters or 'temperature radiators'. Since no surface can absorb more than the total incident radiation, its absorptance cannot exceed unity. A surface having $\alpha = 1$ would absorb all radiation incident on it; there would be no reflected radiation, and the surface (if not incandescent) would appear black. This leads to the concept of a 'blackbody', which is an ideal opaque object that absorbs all incident radiation and emits more radiation at each wavelength than any non-blackbody at the same temperature. The blackbody is thus a perfect absorber and, by definition, a perfect radiator. It is also called a complete radiator, a full radiator, a Planckian radiator, or an ideal radiator.

The emittance of any actual temperature radiator is the ratio of the radiance (for directional emittance) or of the radiant exitance (for hemispherical emittance) of an element of the surface of the radiator to that of a blackbody at the same temperature. Unless spectral emittance (i.e., emittance versus wavelength) is specified, integration over all wavelengths is generally implied.

The Stefan-Boltzmann law arrived at by Stefan (1879) after empirical studies, and by Boltzmann (1884) after theoretical analysis, states that the radiation per unit area emitted by a surface is proportional to the fourth power of its absolute temperature:

$$\mathbf{M} = \epsilon \sigma \mathbf{T}^4 \quad \text{, where} \qquad \text{(eq. 9.1-4)}$$

M = radiant flux emitted per unit area, Wm^{-2}
ϵ = emittance (= 1 for a blackbody)
σ = Stephan-Boltzmann constant, $5.670 \times 10^{-8}\ Wm^{-2}\ K^{-4}$
T = absolute temperature of surface, kelvins

Note that the Stefan-Boltzmann law gives the total radiation per unit area but does not give the spectral distribution of that radiation.

Wien's Displacement law (1898) states that the wavelength of the peak of the spectral distribution curve of blackbody radiation varies inversely as the absolute temperature of the blackbody:

$\lambda_M = \mathbf{b}/\mathbf{T}$,where (eq. 9.1-5)

λ_M = wavelength of maximum radiation, nm
b = Wien's displacement constant, 2.8979 × 10^6 nm-kelvins
T = absolute temperature of blackbody, kelvins

From the above it is seen that the peak of the blackbody distribution curve is 'displaced' or shifted to shorter wavelengths as the temperature is increased.

Planck's blackbody radiation law (1900) is the analytical expression for the empirically-determined spectral distribution of blackbody radiation. Planck employed his concept of radiation in discrete quanta of energy to develop this equation or law of blackbody radiation:

$$\mathbf{M}_\lambda = \frac{\mathbf{C}_1}{\lambda^5 [\exp(\mathbf{C}_2/\lambda\mathbf{T}) - 1]}$$,where (eq. 9.1-6)

$\mathbf{M}_\lambda$ = power radiated per unit area and per unit bandwidth, $W \cdot m^{-2} \cdot nm^{-1}$
λ = wavelength in nanometers
$\mathbf{c}_1$ = first radiation constant, = 3.7418 × 10^{20} $W \cdot m^{-2} \cdot nm^4$
$\mathbf{c}_2$ = second radiation constant, 1.4388 × 10^7 nm • K
exp (**x**) ≡ $\mathbf{e}^{\mathbf{x}}$ **e** = base of natural logs

Linear and logarithmic plots of Planck's equation at various temperatures are shown in Figures 9.1-4 and 9.1-5, respectively.

Radiometric Quantities

Radiometry is the measurement of quantities associated with radiant energy.

A radiometer is an instrument for measuring such quantities which are called radiometric quantities. An ideal radiometer would have a flat spectral response, i.e., equal sensitivity at all wavelengths. Since real radiometers cannot be equally sensitive at all wavelengths, they are designed to have approximately flat responses over specified regions of the electromagnetic spectrum; e.g., the optical spectrum.

Radiometric quantities are identified by the descriptor **radiant**, and are defined in terms of the watt (W), the steradian (sr) and square meter (m^2). The steradian is the unit of solid angle which is a measure of the portion of the total space about a point that is included within a conic surface having its apex at that point. Figure 9.1-6 shows both a generalized conic surface with its apex at a point **P** and a sphere of radius **r** with its center at the point **P**. The solid angle ω included within the conic surface is related to the area **A** of the spherical surface which is subtended by the conic surface as follows:

$\omega = \mathbf{A}/\mathbf{r}^2$ steradians (sr) (eq. 9.1-7)

Since **A** and $\mathbf{r}^2$ are both expressed in squared linear units (e.g., m^2), the solid angle ω and the unit of solid angle (sr) are dimensionless; and since **A** is proportional to $\mathbf{r}^2$, the solid angle ω is independent of the radius of the measuring sphere.

The area of any sphere of radius **r** is $4\pi\mathbf{r}^2$, so that the solid angle subtended by a sphere is $\omega = 4\pi\mathbf{r}^2/\mathbf{r}^2 = 4\pi$ steradians, and the solid angle subtended by a hemisphere is 2π steradians.

Radiant energy, Q, is energy emitted, transmitted, or received in the form of electromagnetic radiation. Preferred units are joules (1J = 1W-sec).

Radiant density, w, is radiant energy per unit volume of the transmitting medium. Preferred units are joules per cubic meter (J/m^3).

Radiant flux, ϕ, or radiant power, is radiant energy emitted, transmitted, or received per unit time; $\phi = d\mathbf{Q}/d\mathbf{t}$. Preferred units are watts (1W = 1J/sec).

Radiant flux density at a surface element is radiant power emitted or received per unit area of the surface. Radiant flux density emitted by a surface is called **radiant exitance**, and radiant flux density incident on a surface is called **irradiance**. Preferred units are watts per square meter (W/m^2).

Radiant exitance, M, is radiant flux density emitted by a surface, or radiant power emitted per unit area of the surface. Preferred units are watts per square meter (W/m^2). Formerly called radiant emittance.

Irradiance, E, is radiant flux density incident on a surface, or radiant power incident per unit area of the surface. Preferred units are watts/square meter (W/m^2).

Radiant intensity, I, in a given direction is the radiant flux or radiant power emitted per unit solid angle in the given direction by a surface element of a radiator: $\mathbf{I} = d\phi/d\omega$, where $d\omega$ is the element of solid angle. Preferred units are watts/steradian (W/sr).

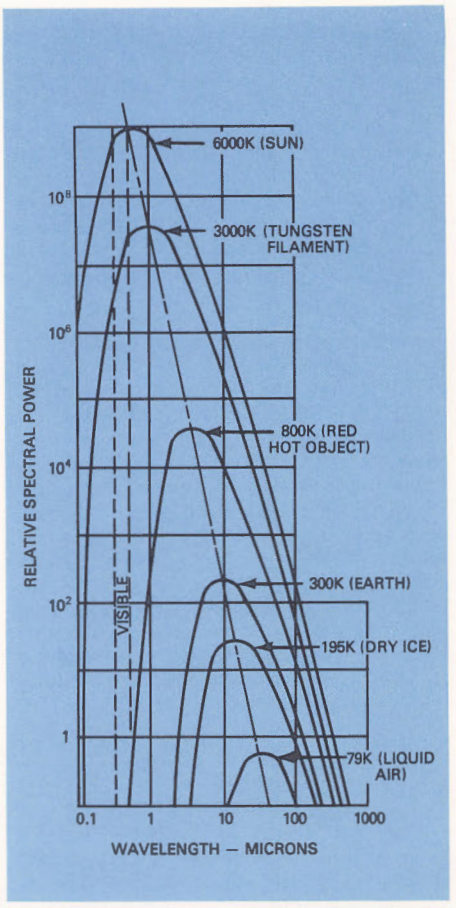


Figure 9.1-5 Logarithmic plots of Planck's equation at various temperatures. Typical object temperatures are given.

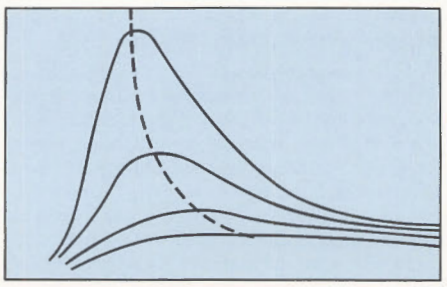


Figure 9.1-4 Linear plots of Planck's equation at various temperatures.

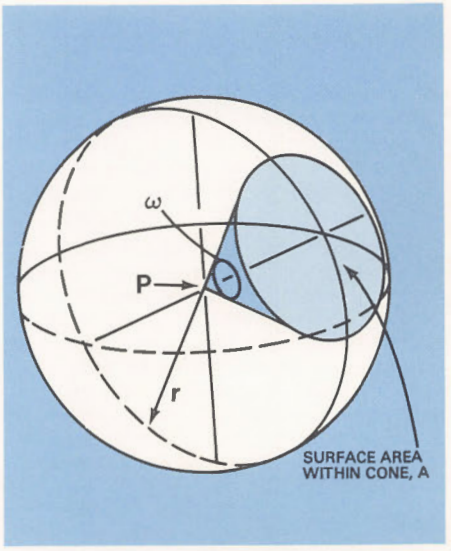


Figure 9.1-6 Definition of solid angle.

9.2 Light

Light is electromagnetic radiation detectable by the human eye, i.e., radiant energy of wavelengths from about 380nm to about 780nm. The sensitivity of the eye is not equal at all wavelengths but varies greatly over the visible spectrum, causing differences in luminance at different wavelengths even for equal radiance (i.e., radiant energy of equal power levels) at those different wavelengths. If the sensitivity of the eye to radiant energy at different wavelengths is plotted against wavelength, it results in a curve called the spectral luminous efficiency curve. Although these curves are quite similar for most observers, they vary somewhat between observers, and they vary for each observer, depending on age, health, viewing conditions, and state of adaptation to light. These spectral luminous efficiency curves are not analytical; i.e., they cannot be represented exactly by any simple equation.

The IES defines light as visually-evaluated radiant energy. To permit objective evaluation of light independent of the idiosyncrasies of individual observers, the CIE has adopted two standard relative spectral luminous efficiency functions derived from measurements on large samples of experimental subjects. These 'standard observer' functions are the photopic spectral luminous efficiency $V(\lambda)$ of the light-adapted eye, and the scotopic spectral luminous efficiency $V'(\lambda)$ of the dark-adapted eye. These non-analytic functions are represented by numbers that are reciprocals of the relative amounts of radiant energy required to produce equal perceived luminances at all wavelengths. The functions $V(\lambda)$ and $V'(\lambda)$ are shown in Figure 9.2-1.

Photopic and Scotopic Vision

The spectral luminous efficiency functions in Figure 9.2-1 represent the relative spectral sensitivities of the two different types of photoreceptors in the retina of the human eye, the rods and cones. The photopic function $V(\lambda)$ of the light-adapted eye represents the relative spectral sensitivity of cones, and the scotopic function $V'(\lambda)$ of the dark-adapted eye represents the relative spectral sensitivity of rods.

Rods and cones have not only different relative spectral sensitivities, but different absolute sensitivities, different threshold sensitivities, different distributions across the retina (and thus across the field of view), and even different color-sensing capabilities.

Cones are densest in the fovea, a spot in the central region of the retina, and their density decreases rapidly from the fovea to the periphery of the retina. Rods are absent from the fovea; their density increases from the region immediately about the fovea to a maximum at about 20 angular degrees from the fovea, and then falls off toward the periphery of the retina. As a result of these distributions, visual acuity is sharpest in the region of the fovea, and becomes less sharp towards the periphery of the retina.

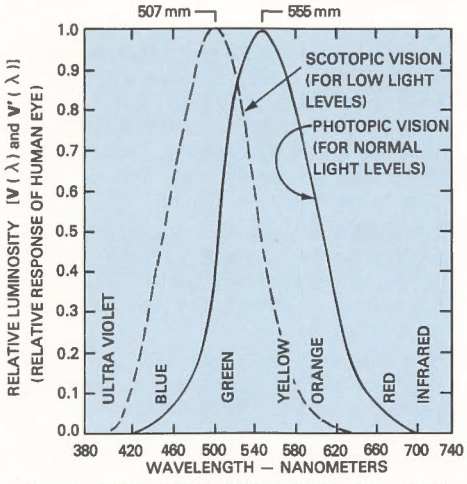


Figure 9.2-1. The CIE relative spectral luminous efficiency functions. The photopic functions $V(\lambda)$ is the spectral luminous efficiency of the light-adapted eye, and the scotopic function $V'(\lambda)$ is the spectral luminous efficiency of the dark-adapted eye.

Rods and cones are both sensitive to luminances in the mesopic range from about 0.01 footlambert to about 1 footlambert. Cones are insensitive in the scotopic range below about 0.01 footlambert, thus dark-adapted vision is accomplished almost entirely by rods and is restricted to the retinal region outside the fovea. Light-adapted vision, which occurs in the photopic range above about 1 footlambert, is accomplished almost entirely by cones.

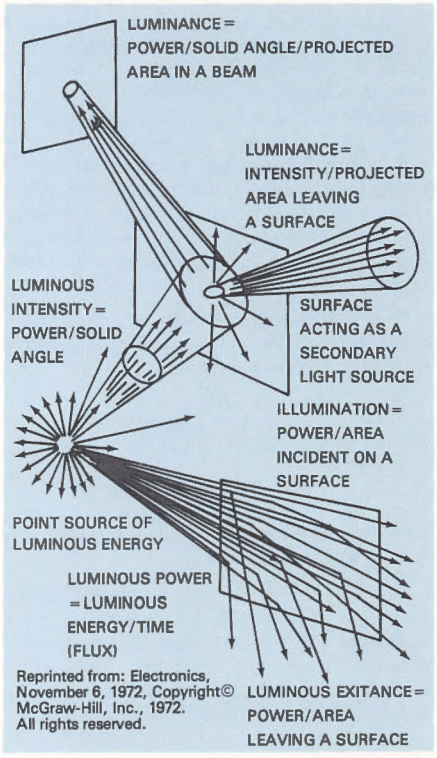

LUMINANCE = POWER/SOLID ANGLE/PROJECTED AREA IN A BEAM
LUMINANCE = INTENSITY/PROJECTED AREA LEAVING A SURFACE
LUMINOUS INTENSITY = POWER/SOLID ANGLE
SURFACE ACTING AS A SECONDARY LIGHT SOURCE
ILLUMINATION = POWER/AREA INCIDENT ON A SURFACE
POINT SOURCE OF LUMINOUS ENERGY
LUMINOUS POWER = LUMINOUS ENERGY/TIME (FLUX)
LUMINOUS EXITANCE = POWER/AREA LEAVING A SURFACE
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Figure 9.2-2 Definitions of photometric quantities.

RADIOMETRIC QUANTITIES: SYMBOLS, DEFINITIONS, AND UNITS

QUANTITY	SYMBOL	DEFINING EQUATION	UNIT	ABBREVIATION
RADIANT ENERGY	**Q**		JOULE	J
RADIANT DENSITY	**w**	$w = dQ/dv$	JOULE PER CUBIC METER	$J \cdot M^{-3}$
RADIANT FLUX	ϕ	$\phi = dQ/dt$	WATT	W
RADIANT FLUX DENSITY AT A SURFACE:				
RADIANT EXITANCE	**M**	$M = d\phi/dA$	WATT PER SQUARE METER	$W \cdot M^{-2}$
IRRADIANCE	**E**	$E = d\phi/dA$		
RADIANT INTENSITY	**I**	$I = d\phi/d\omega$ (ω = solid angle through which flux from point source is radiated)	WATT PER STERADIAN	$W \cdot SR^{-1}$
RADIANCE	**L**	$L = d^2\phi/(d\omega dA \cos\theta)$ $L = dI/(dA \cos\theta)$ (θ = angle between line of sight and normal to surface considered)	WATT PER STERADIAN AND SQUARE METER	$W \cdot SR^{-1} \cdot M^{-2}$

Figure 9.1-7 Summary of radiometric symbols, definitions, and units. (t-time; v-volume)

Photometric Quantities

Photometry is the measurement of quantities associated with luminous radiation, which is electromagnetic radiation evaluated in terms of the spectral sensitivity of the human eye. The basis for such evaluations is usually the CIE photopic spectral luminous efficiency function **V(λ)** of Figure 9.2-1.

If the non-selective radiometer described in Section 9.1 is fitted with a filter having a spectral transmittance curve matching the CIE photopic relative spectral luminous efficiency curve of Figure 9.2-1, the measurements made by the radiometer will be weighted at each wavelength in accordance with the relative spectral sensitivity of the human eye. Such a radiometer is called a photometer, and the quantity it measures is called a photometric quantity. Photometric quantities are usually identified by the descriptor **luminous**, and are defined in terms of the lumen (lm), steradian (sr), and square meter (m^2). The lumen is the photometric unit of luminous flux and is analogous to the radiometric unit of radiant flux, the watt. The steradian is the unit of solid angle which has been defined in Section 9.1 under Radiometric Quantities.

The relationship between all photometric quantities and the corresponding radiometric quantities is given by:

$$\text{photometric quantity} = K_m \int_{380}^{780} \begin{pmatrix}\text{spectral}\\ \text{radiometric}\\ \text{quantity}\end{pmatrix} \bullet V(\lambda)\, d\lambda$$

where K_m is the maximum luminous efficiency factor, 683 lumens per watt.

The various photometric quantities are defined below and are illustrated in Figure 9.2-2. Note that the symbols used for photometric quantities are the same as for the corresponding radiometric quantities. Where it is necessary to distinguish between them, the symbols for radiometric quantities are given the subcript *e* (for electromagnetic) and the symbols for photometric quantities are given the subscript *v* (for visual).

Luminous energy, Q, is light energy (visually-evaluated radiant energy) emitted, transmitted, or received. Preferred units are lumen-seconds (lm-sec) or talbots; lumen-hours (lm-hr) are frequently used in economic analysis.

Luminous density, w, is luminous energy per unit volume of the transmitting medium. Preferred units are lumen-seconds per cubic meter (lm-sec/m^3) or lumen-seconds per cubic foot (lm-sec/ft^3).

Luminous flux, ϕ, or luminous power, is luminous energy emitted, transmitted, or received per unit time: $\phi = dQ/dt$. Units are lumens (lm).

Luminous flux density at a surface is luminous power, or flux, emitted or received per unit area of the surface. Luminous flux density emitted by a surface is called **luminous exitance,** and luminous flux density incident on a surface is called **illuminance.** Preferred units are lumens per square meter (lm/m^2) and lumens per square foot (lm/ft^2).

Luminous exitance, M, is luminous flux density emitted by a surface. Preferred units are lumens per square meter (lm/m^2) and lumens per square foot (lm/ft^2). Formerly called luminous emittance.

Illuminance, E, is luminous flux density incident on a surface. Preferred units are lumens per square meter (lm/ft^2) or lux (lx) and lumens per square foot (lm/ft^2) or footcandle (fc). Formerly called illumination.

Luminous intensity, I, in a given direction is the luminous flux emitted per unit solid angle in the given direction by a surface element of a source: $I = d\phi/d\omega$ where $d\omega$ is the element of solid angle. Preferred units are lumens per steradian (lm/sr) or candelas (cd).

Luminance, L, in a given direction is the luminous intensity per unit area measured normal to the given direction, of flux emitted, transmitted, or received by a surface: $L = dI/(dA \cos\theta)$, where θ is the angle between the given direction and a normal to the surface. A concomitant definition for luminance is $L = d\phi/[d\omega(dA \cos\theta)]$. Preferred units are candelas per square meter (cd/m^2) or candelas per square foot (cd/ft^2). Lumens per square foot and per steradian, and lumens per square meter and per steradian, are equally acceptable. Other occasionally-used units are candelas per square centimeter or stilbs, $1/\pi$ candelas per square meter or apostilbs, $1/\pi$ candelas per square centimeter or lamberts, and $1/\pi$ candelas per square foot or footlamberts; these units are now deprecated. Luminance was formerly called photometric brightness.

The definitions above are summarized in Figure 9.2-3.

From the radiometric definitions given in Section 9.1 and the photometric definitions given above, some further definitions are obtained which are useful for evaluating light sources:

Luminous efficacy of radiant flux is the ratio of total luminous flux to total radiant flux. Units are lumens per watt (lm/W or LPW). For radiation this is the ratio of two outputs: the luminous output (in lumens), and the total radiant output (in watts).

Luminous efficacy of a light source is the ratio of total luminous flux emitted by the light source to the total power input to the light source. Units are lumens per watt (lm/W or LPW). Although the units are the same as for the luminous efficacy of radiant flux, the luminous efficacy of a light source is the ratio of an output (the luminous flux in lumens) to an input (the input power, in watts). The term luminous efficiency was formerly used for this quantity, but the term 'efficiency' is now usually restricted to the ratio of output to input when both are expressed in the same units, and is always a dimensionless number less than unity.

PHOTOMETRIC QUANTITIES: SYMBOLS, DEFINITIONS, AND UNITS

QUANTITY	SYMBOL	DEFINING EQUATION	UNIT	ABBREVIATION
LUMINOUS EFFICIENCY	V	$V = K/K_{maximum}$	NONE (DIMENSIONLESS)	
LUMINOUS ENERGY (QUANTITY OF LIGHT)	Q	$Q = 683\int_{380}^{780} V(\lambda)\, Q(\lambda)\, d\lambda$	LUMEN - SECOND (TALBOT)	LM • S
LUMINOUS DENSITY	w	$w = dQ/dv$	LUMEN - SECOND PER CUBIC METER	LM • SEC • M^{-3}
LUMINOUS FLUX	Φ	$\Phi = dQ/dt$	LUMEN	LM
LUMINOUS FLUX DENSITY AT A SURFACE:				
LUMINOUS EXITANCE	M	$M = d\Phi/dA$	LUMEN PER SQUARE METER LUMEN PER SQUARE FOOT	LM • M^{-2} LM • FT^{-2}
ILLUMINATION (ILLUMINANCE)	E	$E = d\Phi/dA$	FOOTCANDLE (LM/FT^2) LUX (LM/M^2)	FC LX
LUMINOUS INTENSITY (CANDLEPOWER)	I	$I = d\Phi/d\omega$ (ω = solid angle through which flux from point source is radiated)	CANDELA (LUMEN PER STERADIAN)	CD
LUMINANCE (PHOTOMETRIC BRIGHTNESS)	L	$L = d^2\Phi/(d\omega dA \cos\theta) = dI/(dA \cos\theta)$ (θ = angle between line of sight and normal to surface considered)		CD/FT^2, LM/(FT^2 SR) CD/M^2, LM/(M^2 SR)
LUMINOUS EFFICACY	K	$K = \Phi/W$	LUMEN PER WATT	LM • W^{-1}

Figure 9.2-3 Summary of photometric symbols, definitions, and units. (t-time; v-volume)

9.3 Color

Color is that aspect of visual sensation in the photopic range which depends on the relative spectral distribution of radiant energy in the visible spectrum. Identical colors can be produced not only by identical spectral distributions, but by many different spectral distributions. Identical colors produced by different spectral distributions are called metameric colors, or simply metamers.

Definitions of Color

The IES Lighting Handbook (5th edition) has separated definitions for color, color of an object, and color perceived as belonging to an object, as follows:

Color is the characteristic of light by which an observer may distinguish between two structure-free patches of light of the same size and shape.

Object color is the color of the light reflected or transmitted by an object when illuminated by a CIE standard light source and viewed by a CIE Standard Observer under standardized conditions of observation.

Perceived object color is the color perceived to belong to an object, resulting from characteristics of the object, incident light and surround, as well as observer characteristics including but not limited to viewing direction and adaptation. Note that each of the foregoing characteristics may vary both spectrally and directionally.

The three preceding definitions become one when the characteristics of the observer and the conditions of observation are standardized.

Color Vision

Although the sensitivities of both rods and cones vary with wavelength, only the cones are able to distinguish color as such. Rods are completely insensitive to color, and objects viewed with the dark-adapted eye appear gray. The eye is most sensitive to color at luminances in the photopic range where cone vision predominates, and is somewhat less sensitive to color at luminances in the mesopic range where both cones and rods function.

The two major theories of color vision, the Young-Helmholtz three-component theory and the Hering opponent-color theory, both postulate trichromatic processes for sensing color. Thus an observer with normal color vision will be able to match two colors if a set of three independent variables describing one color appears identical to the corresponding set of variable describing the other color when all other factors such as shape, size, gloss, texture, surround, etc., are the same. If the spectral composition of the two colors is identical, the two sets of variables will appear identical under all conditions, and the color match is said to be spectral, unconditional, or non-metameric. However, if the spectral composition of the two colors is different, the two sets of variables will appear identical only under certain conditions, and the match is said to be conditional or metameric.

Color Mixtures

A color mixture is color produced by the combination of other colors. Color mixtures may result from addition or subtraction of colors.

Additive color mixtures are colors produced by combining lights of different colors, simultaneously or in rapid succession. A range of colors (determined by the choice of primaries) may be produced by combining three additive primaries (e.g., a red, a green, and a blue) in various proportions.

Newton (1730) showed that a large range of colors can be matched by the addition of red, green, and blue lights in the correct proportions. In this instance red, green, and blue are called 'primary' colors since they are used to produce the other colors, but they are not unique.

Grassman's Laws state that (1) three colors (spectral power distributions) can match any color by additive mixing, (2) the match continues at all luminance levels, and (3) two lights that appear equal will function the same in all mixes. There are certain requirements such as that no mix of two of the sources can match the third, negative quantities will be required (a negative primary is added to the light being matched rather than to the other primaries), restrictions on luminance levels and field size, requirement of normal color vision etc.

As shown schematically in Figure 9.3-1, addition of red and green lights in the correct proportions can produce yellow light, red and blue lights can produce magenta light, and blue and green lights can produce cyan light. Note that the colors yellow, magenta and cyan are shown on the sides of the color triangle midway between their primaries. Any other color can be produced by combinations of two or three primaries in various proportions, and can be represented by some point inside the triangle. As a limiting case, the addition of correct proportions of all three primaries can produce white light, shown at the center of the color triangle.

Subtractive color mixtures are colors produced by absorption of various wavelengths from white light by means of two or more absorptive colorants (e.g., dyes or pigments), each of which selectively absorbs certain wavelengths that the other colorants reflect or transmit. A wide range of desired colors can be produced by combining three subtractive primary colorants (e.g., magenta, cyan, and yellow, as shown in Figure 9.3-2) in the correct proportions. If the three primaries collectively absorb all wavelengths contained in white light, they will be capable of producing black. Figure 9.3-2 shows that, in color printing for example, cyan printed over yellow produces green; cyan over magenta produces blue; magenta over yellow produces red; and all three primaries printed over each other in any sequence produce black.

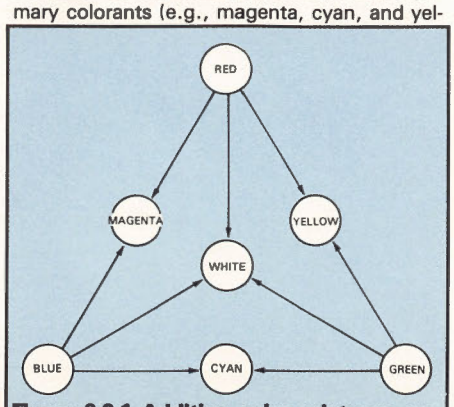


Figure 9.3-1 Additive color mixtures produced by combinations of three lights of the primary colors red, green, and blue.

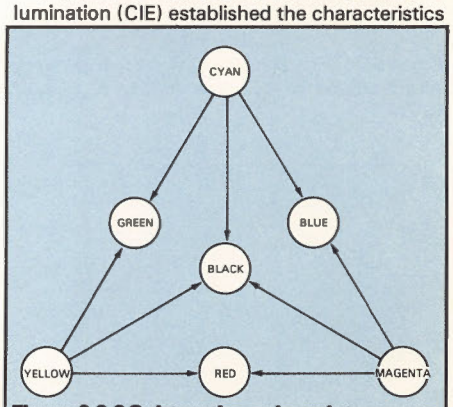


Figure 9.3-2 Subtractive color mixtures produced by combinations of three absorptive colorants of the primary colors magenta, cyan, and yellow.

Colorimetry

Colorimetry is ideally defined as the measurement of color. However, since the purely subjective aspects of perceived color cannot be measured, practical colorimetry is reduced to the matching of colors by eye, or to the measurement of physical phenomena that correlate as closely as possible with perceived color. There are a number of colorimetric systems, almost all of which are based on the principle of trichromacy and thus require the measurement and/or specification of at least three independent quantities to determine a color. In the CIE color system the three variables are the tristimulus values **X**, **Y**, and **Z**. In the Munsell color system the three variables are hue, value, and chroma. The Inter-Society Color Council-National Bureau of Standards (ISCC-NBS) system employs hue, lightness, and saturation, and the Ostwald system uses color content, white content, and black content. These various systems are described below.

CIE Color System

The CIE color system of 1931 defines all metameric pairs of colors in terms of the amounts **X**, **Y**, and **Z** (called the tristimulus values) of three imaginary primary colors required by a standard observer to obtain a (metameric) match. If the tristimulus values of color 1 are $\mathbf{X}_1$, $\mathbf{Y}_1$, $\mathbf{Z}_1$, and the tristimulus values of color 2 are $\mathbf{X}_2$, $\mathbf{Y}_2$, $\mathbf{Z}_2$, then the criterion for color 1 to match color 2 is that the corresponding tristimulus values match:

$$\mathbf{X}_1 = \mathbf{X}_2 \,,\ \mathbf{Y}_1 = \mathbf{Y}_2 \,,\ \text{and}\ \ \mathbf{Z}_1 = \mathbf{Z}_2 \qquad \text{(eq. 9.3-1)}$$

It is always assumed that all other aspects of appearance (e.g. shape, size, gloss, texture, surround, etc.) are identical, so that a color match becomes a match for all aspects of appearance.

In 1931, the International Commission on Illumination (CIE) established the characteristics

of a standard observer for the purposes of color measurement. This standard was expressed in the form of numerical data for the tristimulus values of the spectrum for the average normal human eye under a standard state of adaptation and viewing conditions. The primaries used to determine these tristimulus values are hypothetical since both positive and negative emissions are specified. By choosing hypothetical primaries it is possible to obtain tristimulus values which are positive for all real colors. But being hypothetical, no real lights of these colors exist, and the tristimulus values cannot be experimentally determined but must be calculated.

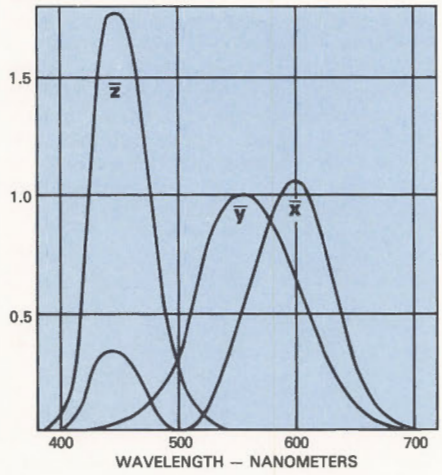


Figure 9.3-3 CIE color-matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$. These are the spectral tristimulus values for an equal-energy spectrum.

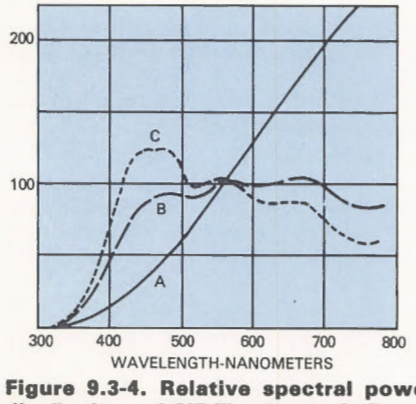


Figure 9.3-4. Relative spectral power distributions of CIE Illuminants A, B, and C.

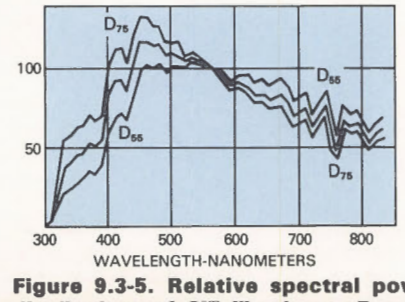


Figure 9.3-5. Relative spectral power distributions of CIE Illuminants D_{55}, D_{65}, and D_{75}.

The tristimulus values for the spectrum are the CIE distribution functions **x, y,** and **z** shown in Figure 9.3-3. The tristimulus values for any source are calculated by multiplying its intensity at each wavelength by the corresponding distribution functions and summing the products over all wavelengths. That is:

$$X = \int S(\lambda)\,\bar{x}\,d\lambda$$
$$Y = \int S(\lambda)\,\bar{y}\,d\lambda \qquad \text{(eq. 9.3-2)}$$
$$Z = \int S(\lambda)\,\bar{z}\,d\lambda$$

where $S(\lambda)$ is the spectral power distribution of the source. The tristimulus values for object colors are obtained in the same manner, with $S(\lambda)$ being replaced by $S(\lambda)\rho(\lambda)$, where $\rho(\lambda)$ is the spectral reflectance (or transmittance) of the object.

The 1931 CIE Standard Observer is a set of tabular data giving the amplitudes of three color-matching functions (which are the tri-stimulus values of an equal-power spectrum) at 10nm intervals in the visible spectrum from 380 to 780nm. These functions, which are designated $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$, and often referred to simply as $\bar{x}$, $\bar{y}$, and $\bar{z}$, are illustrated in Figure 9.3-3. These color-matching functions represent the relative spectral responses of the average human observer over small fields of view. The selection of a set of color-matching functions is arbitrary, and other self-consistent sets could have been specified. However, a major advantage of the 1931 CIE Standard Observer is that the function $y(\lambda)$ is identical to the photopic relative spectral luminosity function $V(\lambda)$ which describes the response of the light-adapted human eye to total illumination. The 1964 CIE Supplementary Observer is represented by three color-matching responses of the average human observer over larger fields of view.

CIE Standard Illuminants. Illuminants are standard light sources having specified spectral power distributions. The following illuminants are specified for the CIE color system. Illuminant A is a tungsten-filament lamp operating at a color temperature of 2856K and approximating a blackbody at that temperature. Illuminant B approximates noon sunlight having a correlated color temperature of about 4874K. It is obtained by a combination of Illuminant A and a liquid filter. Illuminant C approximates the daylight combination of direct sunlight and clear sky, having a correlated color temperature of about 6774K. It is obtained by a combination of Illuminant A and a different liquid filter. Figure 9.3-4 shows the relative spectral power distributions of CIE Illuminants A, B, and C.

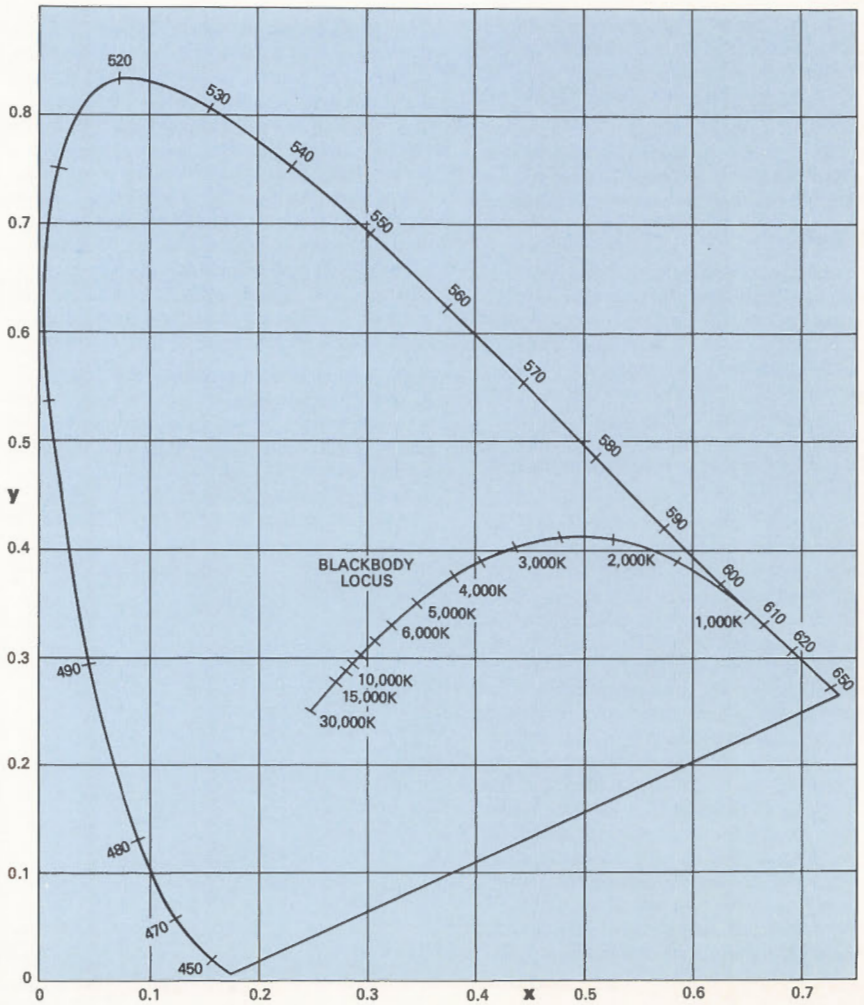


Figure 9.3-6. 1931 CIE (x,y) chromaticity diagram showing locus of spectrum colors (nm) and Planckian locus of blackbody chromaticities at various temperatures.

Illuminants D_{55}, D_{65}, and D_{75} approximate various types of daylight. D_{65} approximates daylight at 6500K, etc. These illuminants are specified in terms of spectral power distributions tabulated in CIE Document 15, but there are no simple combinations of lamps and filters for generating them as is the case with Illuminants A, B, and C. The relative spectral power distributions of Illuminants D_{55}, D_{65}, and D_{75} are shown in Figure 9.3-5.

The CIE (x,y) chromaticity diagram shown in Figure 9.3-6 is a convenient graphical method for presenting color data. From the measured or calculated tristimulus values **X, Y,** and **Z** of a color, three chromaticity coordinates **x, y,** and **z** can be determined as follows:

$$x = \frac{X}{X+Y+Z}, \quad y = \frac{Y}{X+Y+Z}, \quad z = \frac{Z}{X+Y+Z} \qquad \text{(eqs. 9.3-3)}$$

From the above it can be seen that $x + y + z = 1$, so that any two chromaticity coordinates determine the third which is therefore not an independent variable. The coordinates **x** and **y** are commonly used to present chromaticity, but since the principle of trichromacy requires three independent variables to define color completely, a third independent quantity is required. This is conventionally chosen to be the tristimulus value **Y.**

Shown on the CIE (**x,y**) chromaticity diagram of Figure 9.3-6 are two significant curves; the locus of pure spectral colors, and the locus of blackbody chromaticities.

Color temperature of a light source is the absolute temperature (in kelvins) of a blackbody source having a chromaticity equal to that of the light source. A blackbody is red at temperatures near 1000K, yellow at 3000K, white (neutral) at about 5000K, and pale blue at 8000K to 10,000K. Since the chromaticities of blackbodies are determined by their spectral power distributions which are given as functions of temperature by Planck's equation, the locus of blackbody chromaticities on the CIE (**x,y**) chromaticity diagram is called the Planckian locus. This locus is shown in Figures 9.3-6 and 9.3-7. Chromaticities represented by points on the Planckian locus may be specified by color temperatures, but chromaticities represented by points not on the Planckian locus may be specified only by approximate equivalents called correlated color temperatures.

Correlated color temperature of a light source whose chromaticity is not on the Planckian locus is the absolute temperature (in kelvins) of a blackbody whose chromaticity most nearly approximates that of the light source. Correlated color temperatures of points near but not on the Planckian locus can be determined from CIE (**x,y**) chromaticity diagrams on which are plotted lines of constant correlated color temperature called isotemperature lines, as shown in Figure 9.3-7. These lines are plotted at equal intervals of reciprocal color temperature which express equal color differences on the Planckian locus better than do equal intervals of color temperature. The unit of reciprocal color temperature is the mired (pronounced my'red) or micro-reciprocal degree (1 mired = 10^6/color temperature in kelvins). A difference of 1 mired indicates approximately the same color difference anywhere on the color temperature scale above 1800K, even though 1 mired corresponds to a difference of about 4 kelvins at 2000K and to a difference of about 100 kelvins at 10,000K.

Color Rendering Properties of Light Sources

The colors of objects may be significantly different when viewed under different light sources depending on the spectral power distributions of the light from those sources. It is necessary, therefore, to have a means of rating the color-rendering properties of light sources in comparison to those of some standard. The CIE has developed two such means of rating color-rendering properties of light sources; the color-rendering index (CRI or **R**), and the color preference index (**R_p**). The methods by which these indices are obtained are beyond the scope of this handbook, and the reader is referred to the texts on color listed in the bibliography, Section 9.7.

Color rendering index, R (or CRI) of a light source is a measure of the colorimetric shift of perceived colors of test objects (e.g., certain Munsell color chips) illuminated by the source from that of the perceived colors of those test objects when illuminated by a standard or reference source of similar chromaticity. This index is useful for the critical viewing of colored objects. A light source with a color rendering index between 90 and 100 is generally considered to have a color rendering ability close enough to that of the reference source to be a match for practical commercial purposes. Note that color rendering index is not absolute; a daylight fluorescent lamp at 6500K and a warm-white fluorescent lamp at 3000K may have the same color rendering index.

Color preference index, R_p, of a light source is a measure of the colorimetric shift of perceived colors of test objects illuminated by the source from some preferred chromaticity (rather than from the true chromaticity of the test objects when illuminated by a reference source as in measurement of color rendering index). Unlike the color rendering index, the color preference index of a light source takes into account the direction of the colorimetric shift, which has been found to be of importance in esthetic evaluations of color.

Color Order Systems

The CIE systems of colorimetry, color rendering index, and color preference index attempt objective evaluations of colors by measurements which can be reduced to numbers. Most other color systems rely on subjective matching of colors to colored material samples such as cards, chips, or charts. These 'color order systems' are of three major types: colorant mixture systems, color mixture systems, and color appearance systems.

Colorant mixture systems employ limited numbers of dyes or pigments which are blended in systematically varied proportions and used to color samples. The Plochere Color System, for example, consists of 1,248 painted color cards representing all possible combinations of 26 hues, 6 shades, and 8 tints.

Color mixture systems employ samples painted to match the colors produced by mixtures of three primaries (e.g., by the addition of colored lights). Most color mixture systems are based on the Ostwald Color System, which postulates a white content, a black content, and a color content, the sum of which is unity. The system is generally based on 24 equally-spaced hues.

Color appearance systems employ color samples representing uniform steps of hue, saturation, and lightness, as perceived by an observer with normal color vision. The two major color appearance systems are the DIN (Deutsche Industrie Norm) and Munsell color systems. The Munsell system identifies color in terms of hue, value, and chroma. Hue is the attribute that determines whether the color is red, yellow-red, green-yellow, green, blue-green,

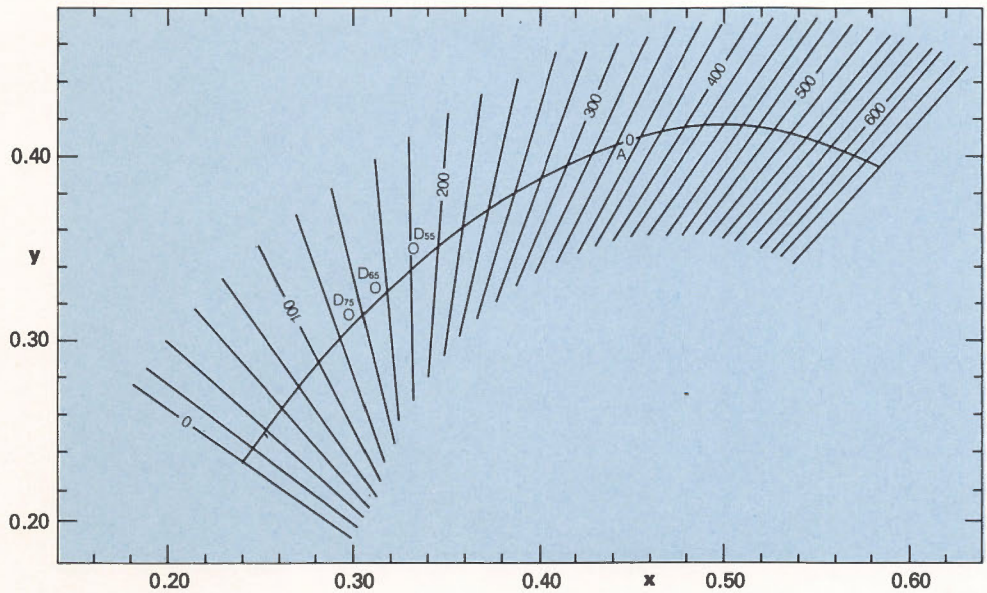


Figure 9.3-7 CIE (x,y) chromaticity diagram showing Planckian locus of blackbody chromaticities and lines of constant correlated color temperature (isotemperature lines) at intervals of 10 microreciprocal degrees (mireds).

blue, blue-purple, purple, or red-purple. These ten colors are arranged equidistantly around a circle, and the spaces between them are subdivided into ten visually equal steps numbered 1 through 10. The notation is a number and the initial(s) of the hue name, e.g., 5GY. The Munsell value indicates the lightness or darkness with respect to a neutral gray, in ten steps from 0/ for absolute black to 10/ for absolute white. The Munsell chroma indicates the departure of a given hue from a neutral gray of the same value, from /0 for a neutral gray out to /10 or more, depending on the strength of the color.

The complete Munsell notation for a color is written in the form: hue value/chroma. For example, 5R6/14 (read "five red six, fourteen") indicates a color of hue = 5R, value = 6, and chroma = 14.

9.4 Optical Methods of Light Control

The light emitted by lamps must often be controlled and even modified to achieve desired spatial and spectral distributions for specific applications. Such results may be achieved by employing the optical phenomena of reflection, refraction, diffusion, absorption, and interference.

Basic Optical Phenomena

Reflection is the process by which light incident on the surface of a medium is returned to the incident side. Reflection may be specular, spread, diffuse, or a composite of these, and may also be spectrally selective or non-selective. Reflection from the front of a transmissive medium is called front-surface or first-surface reflection, and reflection from the rear surface (after passage through the medium) is called second-surface reflection. Obviously, reflection from the surfaces of opaque media is always first-surface reflection. Various types of reflection are illustrated in Figure 9.4-1.

Specular reflection is reflection from a polished surface and obeys the law of reflection. The incident and reflected rays, and the normal to the surface at the point of incidence, all lie in one plane (called the plane of incidence); the angle of reflection equals the angle of incidence as shown in Figure 9.4-1(a). Specular reflectors may be made of almost any material (e.g. metal, glass, plastic) with a surface that can be smoothed (e.g. by casting, forming, or polishing) and sometimes coated (e.g. by electroplating or vacuum deposition with aluminum, dielectric layers, etc.). The reflectance may be high as with aluminum, or low as with clear glass.

Spread reflection is reflection from a depolished (e.g., brushed or etched) or figured (e.g., corrugated, hammered, peened, dimpled, or pebbled) surface, which spreads a parallel beam of incident rays but retains some directionality as shown in Figure 9.4-1(b).

Diffuse reflection is reflection from a matte surface (e.g., an etched or ground surface, or one covered with minute, randomly-oriented crystals or particles of pigment). A perfectly diffusing surface obeys Lambert's cosine law, i.e., the luminous intensity of the reflected ray is proportional to the cosine of the angle of reflection, so that the luminance of the surface is independent of the direction from which the surface is viewed. Diffuse reflection is illustrated in Figure 9.4-1(c) and 9.4-1(d).

Mixed reflection does not fall in the general categories of specular, spread, and diffuse reflection, as shown in Figure 9.4-1(e).

Spectrally-selective reflection occurs in the dichroic cold mirrors and hot mirrors which have been discussed in Section 8.0.

Refraction or bending of oblique rays of light occurs at all interfaces between media of different refractive indices. A ray passing through one homogeneous medium of index $\mathbf{n_1}$ and entering a second homogeneous medium of index $\mathbf{n_2}$ will travel in straight lines within the media, but will be bent at the interface between the two media in accordance with Snell's law of refraction, i.e., the incident and refracted rays and the normal to the interface at the point of incidence lie in one plane (called the plane of incidence), and the angles of incidence **(i)** and refraction **(r)** are related as follows:

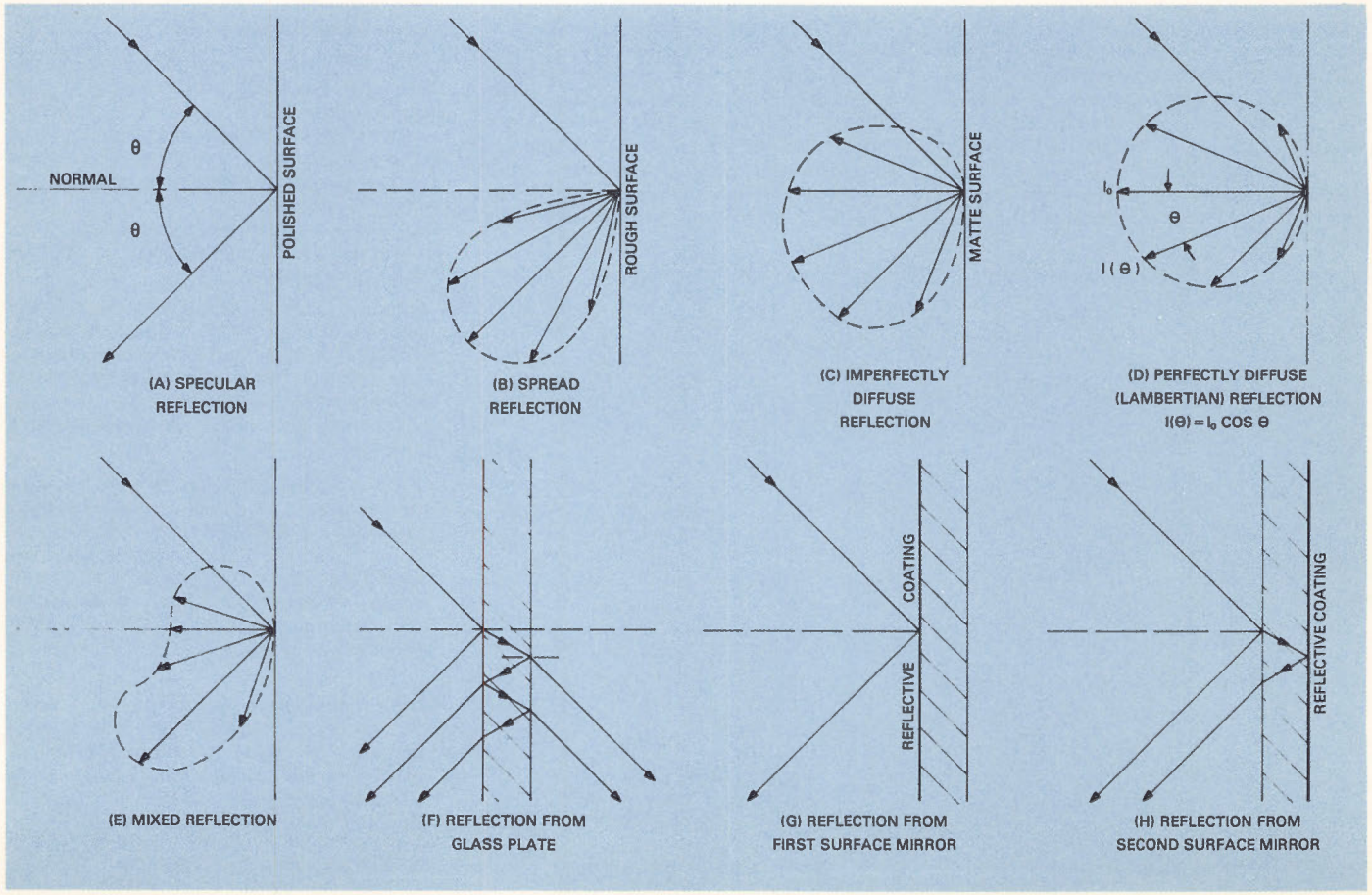


Figure 9.4-1 Types of Reflection.

$n_1 \sin i = n_2 \sin r$, where (eq. 9.4-1)

n_1 = refractive index of first medium
i = angle of incidence of ray at interface
n_2 = refractive index of second medium
r = angle of refraction of ray at interface

The basic phenomena of refraction are illustrated in Figure 9.4-2, which shows: (a) a ray passing from a less-dense to a more-dense medium; (b) a ray passing from a more-dense medium to a less-dense medium; and (c) a ray passing from air to air through a plane-parallel glass plate.

A ray leaving a high-index medium and entering a low-index medium at a sufficiently large angle from the normal will undergo total internal reflection (TIR) within the high-index medium. Total internal reflection is an essentially lossless process. It is illustrated in Figure 9.4-2(d). The critical angle θ_C above which TIR occurs is:

$\theta_C = \arcsin(n_2/n_1)$, (eq. 9.4-2)
where $n_2 < n_1$

Diffusion is the process by which beams of light are spread in many directions by irregular reflection and refraction from microscopic inhomogeneities within a transmitting medium, or from microscopic imperfections of a reflecting surface. Diffuse reflectors were described under reflection.

Absorption causes the intensity of transmitted or reflected light to be less than that of the incident light. Equal absorption at all wavelengths is called non-selective absorption and generally does not cause color effects. Different amounts of absorption at different wavelengths is called selective absorption and causes the colors of most colored objects. The absorbed energy generally appears as heat in the absorbing material.

Interference has been discussed in Section 8.0.

Basic Optical Elements

The basic optical elements used in light control are mirrors, lenses, and prisms.

Mirrors may be plane but they may be curved to provide optical power. The surface may be cylindrical, a surface of revolution, or a general three-dimensional surface. Conic sections, especially parabolic and elliptical, are frequently used for three reasons. They are easy to specify; they are easy to understand for the hypothetical point source; and they are often sufficiently close to an optimum contour to justify the simplicity.

The optical characteristics (eg., light redistribution and degree of diffusion) produced by such reflectors can be controlled by means of their shape and depth, and modified by treating their reflecting surfaces to give specular, spread, diffuse, or mixed reflection. As described in Section 10, conic-section reflectors are employed in many spotlights and floodlights as well as in Abbe illumination systems for transparency projection.

Prisms are used to bend or redirect light rays. There are two major types, reflecting prisms and refracting prisms.

Reflecting prisms frequently employ the phenomenon of total internal reflection which, from equation 9.4-2, occurs in most glasses ($n = 1.5$) at internal angles of incidence greater than a critical angle of about 41.8°. For this reason, 45°/45°/90° prisms are commonly used as reflecting prisms because the 45° internal reflection exceeds the critical angle at which total internal reflection occurs. Figure 9.4-3 shows how a 45°/45°/90° prism can be used to redirect light through 90° as in periscopes, through 180° as in retroreflectors, and through 360° as in prism binoculars. In reflecting prisms the angles through which the light is redirected are independent of the wavelength even though the index of refraction of the glass varies with wavelength, as long as the light enters and leaves the prism near the normal to the air-glass surface.

Refracting prisms, as shown in Figure 9.4-4, cause dispersion of light into spectra showing the component colors. Dispersion occurs because the angle of deviation is a function of the index of refraction, which varies with wavelength. Light control is often achieved by use of many small prisms arranged in patterns to give desired different distributions in vertical and horizontal planes. If the angle of deviation is small or if light from many such prisms overlap, dispersion effects are insignificant. Such prism arrays are used in automobile headlight faceplates, and in luminaires of all types.

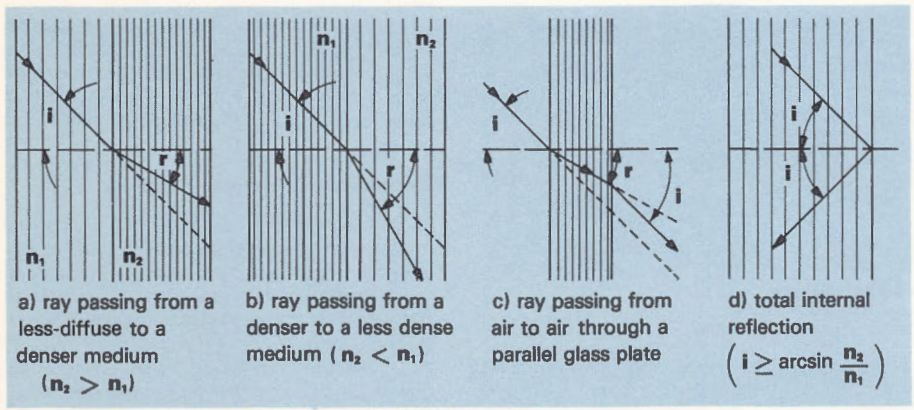

i
r
n_1
n_2
a) ray passing from a less-diffuse to a denser medium ($n_2 > n_1$)
b) ray passing from a denser to a less dense medium ($n_2 < n_1$)
c) ray passing from air to air through a parallel glass plate
d) total internal reflection ($i \geq \arcsin \frac{n_2}{n_1}$)

Figure 9.4-2 Refraction.

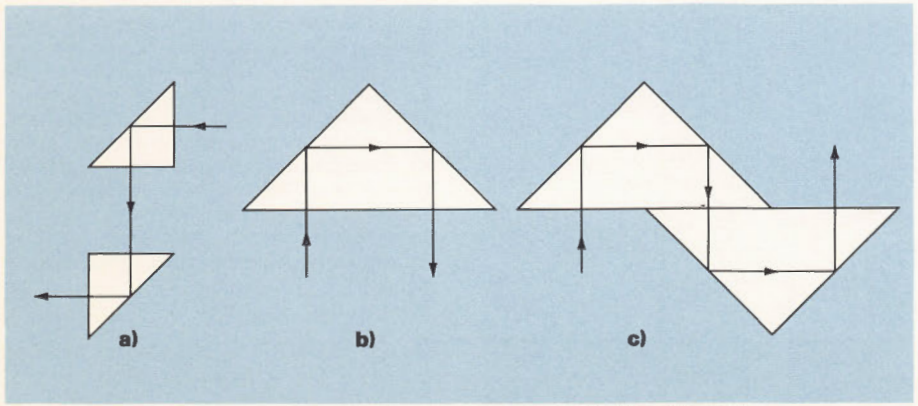


Figure 9.4-3 45°/45°/90° reflecting prisms used to redirect light through (a) 90°, (b) 180°, (c) 360°.

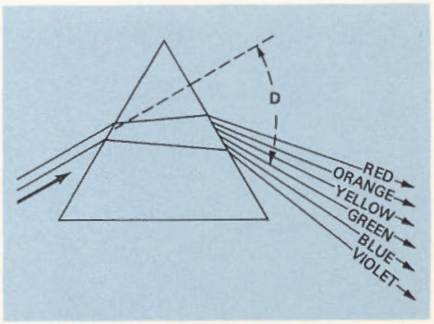


Figure 9.4-4 Refracting prism, showing dispersion of white light into component colors because the angle of deviation D (shown for green light) varies with wave length.

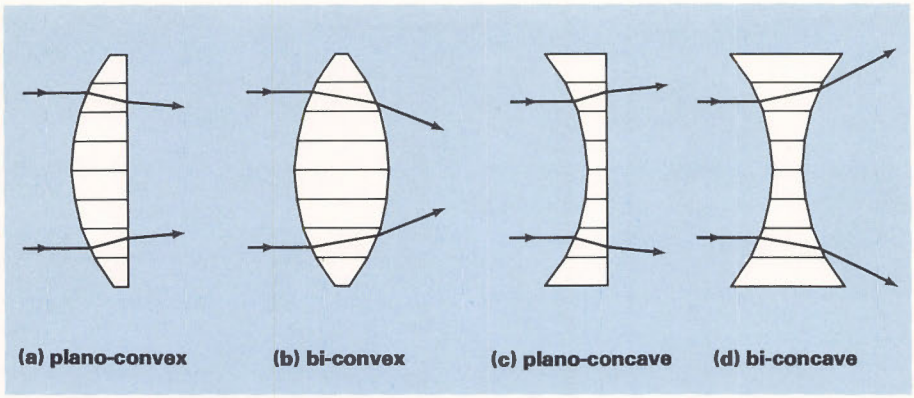


Figure 9.4-5 Types of simple lenses, showing derivation from truncated prisms.

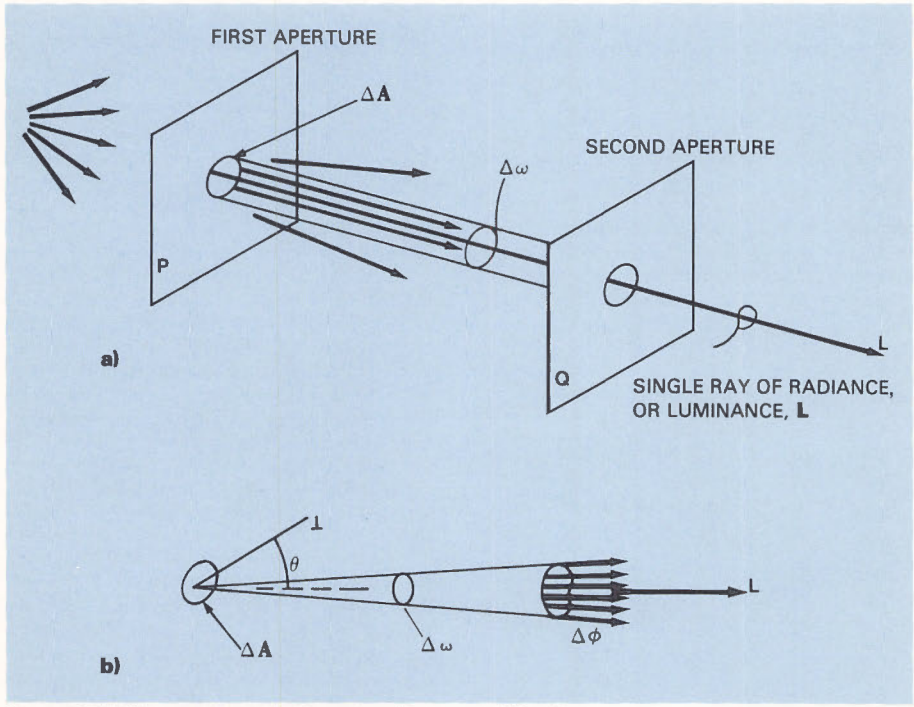


Figure 9.5-1 Geometric definition of radiance and illuminance.

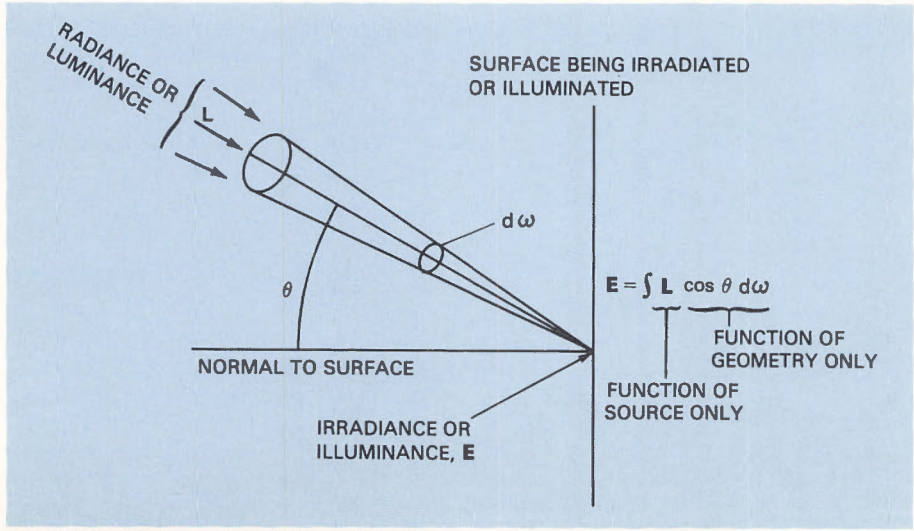


Figure 9.5-2 Geometric definition of irradiance and illuminance.

Lenses with plane and spherical surfaces can be explained in a simple manner by representing the lens with truncated prisms as shown in Figure 9.4-5. The plano-convex and bi-convex lenses, which cause convergence of light rays, are called positive lenses. The plano-concave and bi-concave lenses, which cause divergence of light beams are called negative lenses. All spherical lenses have image-forming imperfections such as spherical aberration, coma, chromatic aberration, astigmatism, curvature, and distortion. Most of these aberrations are usually of little importance in light control systems, such as Kohler illumination systems for transparency projection, where combinations of a few simple lenses are used as 'condensers'. Lenses with aspherical surfaces are sometimes used in such systems.

9.5 Limits of Optical Illumination Systems

Optical systems may be separated into two major categories: optical information systems, including image-forming systems such as cameras, copiers, and other devices that transmit or process information in terms of the spatial distribution of optical radiation; and optical power transfer systems, including optical condensers, collimators, and other optical systems for the control and utilization of optical radiation. Optical devices such as slide and film projectors include both types of optical systems: an optical power transfer system (the optical condensing system) collects the light from a source and projects it onto one side of a transparency which, in turn, spatially modulates the luminance (and, in color transparencies, the spectral content) of the light it transmits; an optical processing system (the projection lens) projects onto a screen the spatially-modulated light beam representing the image of the transparency.

Optical Power Transfer Systems

The following paragraphs are concerned mainly with optical power transfer systems and with the selection and application of sources of optical radiation for use in such systems. If an optical power transfer system handles radiation having a wider spectral content that the visible (e.g., infrared, in applications such as thermal copying; and ultraviolet, in photochemical applications), that radiation must be measured by a radiometer calibrated in radiometric units based on the watt. If the optical power transfer system handles only visible radiation (i.e., light) intended to be sensed by the human eye, that radiation must be measured by a photometer (i.e., a radiometer with a spectral sensitivity approximating that of the human eye) calibrated in photometric units based on the lumen. Luminous evaluation is frequently used in non-visual systems (e.g., lumens in photographic processes) with consistent results if various implicit conditions are met, but with inconsistent or anomalous results if the spectral restraints are ignored.

Radiance and Luminance

The most suitable way of dealing with radiant power is the method of geometrical optics which deals with rays of optical radiation. A single ray has the property designated radiance (for optical radiation) or luminance (for visible radiation), both of which are represented by the symbol **L**. Conceptually, to find **L** for a single ray, we assume an extended source from which rays are emitted in many directions, as in Figure 9.5-1(a). A thin plate (P) with a small aperture placed as shown will block all the rays it intercepts from the source except for those rays that pass through the aperture. The number of rays passing through the aperture are proportional to the area of the aperture and can be reduced by decreasing the aperture to a pinhole*. The aperture approximates a point source radiating a small fan of light rays. A second aperture plate (Q) placed as shown will in turn block all the rays it intercepts from the first aperture except for those rays that pass through the second aperture. The number of rays passing through can be decreased by reducing the second aperture until, at the limit, a single ray can be isolated.

The power in a single ray is equal to the flux per unit projected area and per unit solid angle as follows (see Figure 9.5-1(b)):

$$\mathbf{L} = \lim_{\substack{\Delta \mathbf{A} \to 0 \\ \Delta\omega \to 0}} \frac{\Delta\phi}{(\Delta \mathbf{A}\cos\theta)\,\Delta\omega} \qquad \text{(eq. 9.5-1)}$$

L = power in a single ray
$\Delta\phi$ = flux in the small cone
$\Delta \mathbf{A}$ = actual area of first aperture
θ = angle of tilt between ray and normal to plane of aperture
$\Delta \mathbf{A}\cos\theta$ = projected area of first aperture
$\Delta\omega$ = solid angle of small cone

Taking the limit of equation 9.5-1 as $\Delta \mathbf{A}$ and $\Delta\omega$ both approach zero, we get:

$$\mathbf{L} = \frac{d^2\phi}{d\omega\, d\mathbf{A}\cos\theta} \qquad \text{(eq. 9.5-2)}$$

In the equations 9.5-1 and 9.5-2, if the flux ϕ is radiant flux ϕ_e in watts, the quantity **L** is the radiance $\mathbf{L}_e$ in watts; and if the flux ϕ is luminous flux ϕ_v in lumens, then the quantity **L** is the luminance $\mathbf{L}_v$ in lumens.

Abbe's Law states that the radiance or luminance of a ray is invariant in any continuous, homogeneous, lossless medium. Radiance and luminance are therefore useful quantities for the analysis and design of optical power transfer systems and for determination of irradiance or illuminance levels produced by those optical power transfer systems on surfaces.

Irradiance and Illuminance

The purpose of most optical power transfer systems is to irradiate or illuminate surfaces such as that of a photosensitive material in a copier, a transparency in a slide or film projector, or a projection screen. We are therefore interested in the flux or power delivered by the optical system to each unit area of the surface. Radiant power incident per unit area (W/m²) is called radiant flux density or irradiance. Luminous power incident per unit area (lm/m² or lm/ft²) is called luminous flux density or illuminance (formerly illumination). Both irradiance and illuminance are represented by the symbol **E**. These quantities can be determined if the radiance or luminance **L** of the incident radiation and the geometry of the incident radiation are known.

The irradiance or illuminance on a surface can be determined as in Figure 9.5-2 which shows a converging cone of rays incident on a surface. The rays have the radiance or luminance **L**, the axis of the cone is at an angle θ from the normal to the surface, and the solid angle of the cone is $d\omega$. The irradiance or illuminace **E** on the surface is given by:

$$\mathbf{E} = \int \mathbf{L}\cos\theta\, d\omega, \qquad \text{(eq. 9.5-3)}$$

which is true in all cases. The inverse square law, which is only an approximation applicable in certain situations, can be derived from equation 9.5-3. If the solid angle $d\omega$ of the converging cone of incident radiation is small, a simple and useful approximation of equation 9.5-3 can be obtained by letting $d\omega = \Delta\omega$ and by assuming that **L** is constant over that solid angle. Equation 9.5-3 then can be approximated by:

$$\mathbf{E} \cong \mathbf{L}\cos\theta\Delta\omega \qquad \text{(eq. 9.5-4)}$$

An advantage of the definition of equation 9.5-3 is that the integrand is the product of two independent factors: radiance or luminance which depends only on the source, and the factor ($\cos\theta d\omega$) which depends only on the geometry of the incident radiation. Since each factor has an inherent upper limit, it is thus possible to predict the maximum level of irradiance or illuminance that is theoretically possible in any optical power transfer system regardless of its form. Since the geometric component has some maximum value, the maximum illumination of a surface is ultimately limited by the luminance of the source regardless of the optical system employed.

Consider a source of **L** as illustrated in Figure 9.5-3. An ideal lossless optical system directs rays from the source onto element P from all directions within a hemisphere. Since **L** is a constant, it can be taken outside the integral, giving:

$$\mathbf{E}_{max} = \mathbf{L}\int_0^{2\pi} \cos\theta\, d\omega = \pi\mathbf{L}, \qquad \text{(eq. 9.5-5)}$$

where $\mathbf{E}_{max}$ is in lm/m² and **L** is in cd/m², or $\mathbf{E}_{max}$ is in W/m² and L is in W/(sr m²), etc. For the

*This presentation is heuristic rather than rigorous. Needless to say, there are various postulates assumed to avoid such real problems as the diffraction that occurs at small apertures, etc.

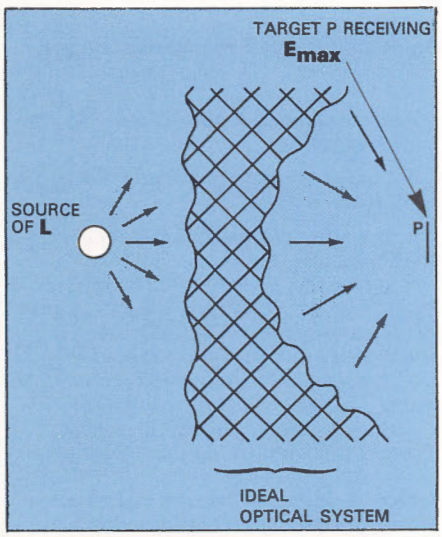
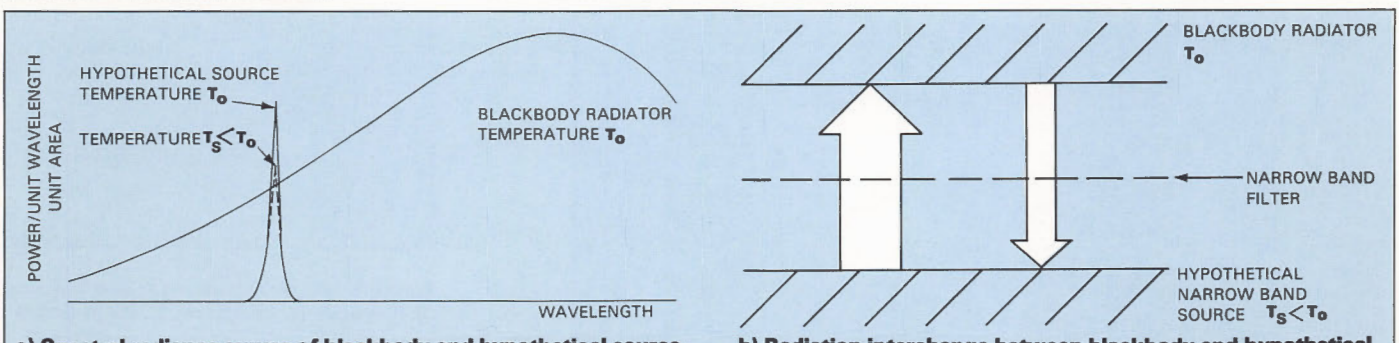


Figure 9.5-3 Diagram for obtaining theoretical maximum illuminance E_{max} on a surface from a source of luminance L.



a) Spectral radiance curves of blackbody and hypothetical source.

b) Radiation interchange between blackbody and hypothetical source through a narrowband transmission filter.

Figure 9.6-1 Conceptual experiment comparing a blackbody at temperature T_o with a hypothetical narrowband source at temperature $T_S < T_o$.

special case of a lambertian source, integration determines that $\mathbf{M} = \pi \mathbf{L}$; thus $\mathbf{E_{max}}$ is equal to the exitance **M**.

Equation 9.5-5 provides a simple, rapid means of estimating the maximum possible illuminance caused by a source in the absence of losses. Practical systems have attenuation losses and thus can never attain this limiting geometric efficiency.

9.6 Limitations of Light Sources

The state-of-the-art luminance and efficacy of typical light sources (shown in Figure 1.0-9) is ultimately limited by various physical phenomena. One theoretical limit of all light sources is the spectral power distribution of the blackbody, which is an ideal radiator that emits more radiant flux per unit area, per unit solid angle, and per unit wavelength interval than does any real radiator at the same temperature. This limit can be demonstrated by a conceptual experiment which assumes that there exists a source of temperature $\mathbf{T_o}$ which can radiate more energy in some narrow wavelength band than can a blackbody of the same temperature as shown in Figure 9.6-1a. It should then be possible to reduce the temperature of the hypothetical source to some temperature $\mathbf{T_s}$ which is less than $\mathbf{T_o}$, at which the hypothetical source will still emit more than the $\mathbf{T_o}$ blackbody in the narrow band. If, as in Figure 9.6-1b, we interpose between the hypothetical source of temperature $\mathbf{T_s} < \mathbf{T_o}$ and the adjacent blackbody of temperature $\mathbf{T_o}$ a narrowband filter which passes the wavelengths emitted by the hypothetical source, more energy would be radiated from the hypothetical source to the blackbody than would be radiated in the reverse direction. This would cause a net transfer of energy from the lower temperature $\mathbf{T_s}$ to the higher temperature $\mathbf{T_o}$ without external sources of energy, thus violating the second law of thermodynamics. The obvious conclusion is that the original hypothesis was false, and that there can exist no source which radiates more per unit area, per unit solid angle, and per unit wavelength than does a blackbody at the same temperature.

From the conceptual experiment described above, it is seen that the blackbody spectral radiance curve thus represents a theoretical upper limit to the output of any light source. Furthermore, this theoretical upper limit can be calculated from Planck's blackbody radiation law (Equation 9.1-6) for any source of known temperature.

Figure 9.6-2 shows the spectral radiance curves of blackbodies at various temperatures from 2000K to 6000K. As the temperature rises, the radiance (output at all wavelengths) and luminance (photopically evaluated output in the visible) both increase, and the peak wavelength shifts to shorter wavelengths in accordance with Wien's displacement law (equation 9.1-5). At temperatures below about 6000K the peaks of the curves are in the infrared, at about 6000K the peak of the curve is in the visible, and at temperatures above about 6000K (not shown in Figure 9.6-2) the peaks are in the ultraviolet. The luminous efficacy of radiant flux (which is defined as the ratio of total luminous flux to total radiant flux) from the blackbody is thus seen to increase with temperatures up to about 6000K and then to decrease at higher temperatures.

Tungsten-Filament Incandescent Lamps

The 2750K blackbody curve in Figure 9.6-2 is of interest because the common 100W tungsten-filament incandescent household lamp operates at about that temperature. The 2750K blackbody curve is shown again in Figure 9.6-3 along with the spectral radiance curve of tungsten at 2750K. The difference between the two curves occurs because tungsten is a selective radiator, the spectral emittance of which is about 0.43 in the visible and decreases at longer wavelengths, as shown in Figure 9.6-4. The integrated total emittance over all wavelengths is about 0.33. Note that, because of the manner in which its spectral emittance varies, tungsten has about 30% higher luminous efficacy (lumens per radiated watt) than a blackbody of the same temperature, although the luminance (lumens) of tungsten is only about 43% of that of a blackbody.

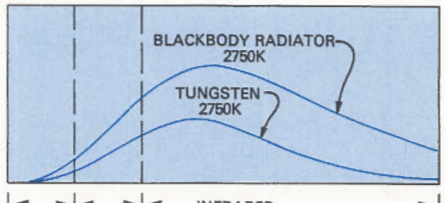


Figure 9.6-3 Spectral radiance curves for tungsten and blackbody, both at 2750K.

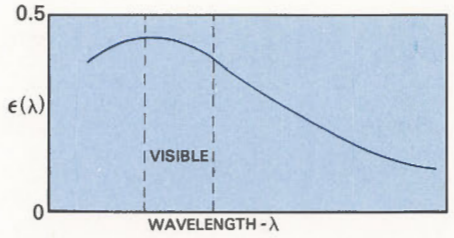


Figure 9.6-4 Spectral emittance of tungsten.

A simplified derivation of the foregoing statement is as follows:

a. The power radiated by tungsten is $\mathbf{P}_{tung} = \epsilon\sigma\mathbf{T}^4$, where $\epsilon = .33$

b. The power radiated by a blackbody is $\mathbf{P}_{bb} = \sigma\mathbf{T}^4$ (Because $\epsilon = 1$)

c. The ratio of the radiated powers is $\mathbf{P}_{tung}/\mathbf{P}_{bb} = \epsilon\sigma\mathbf{T}^4/\sigma\mathbf{T}^4$. Since both temperatures are the same, this reduces to $\mathbf{P}_{tung}/\mathbf{P}_{bb} = \epsilon = .33$, so that $\mathbf{P}_{tung} = 0.33\,\mathbf{P}_{bb}$.

d. The luminance of tungsten is about 0.43 that of a blackbody, or $\mathbf{L}_{tung} = 0.43\,\mathbf{L}_{bb}$.

e. The luminous efficacy of tungsten in lumens per radiated watt is therefore $\mathbf{L}_{tung}/\mathbf{P}_{tung} = .43\mathbf{L}_{bb}/.33\mathbf{L}_{bb} = .43/.33 = 1.3$, which, is about 130% that of a blackbody, or 30% greater than that of a blackbody.

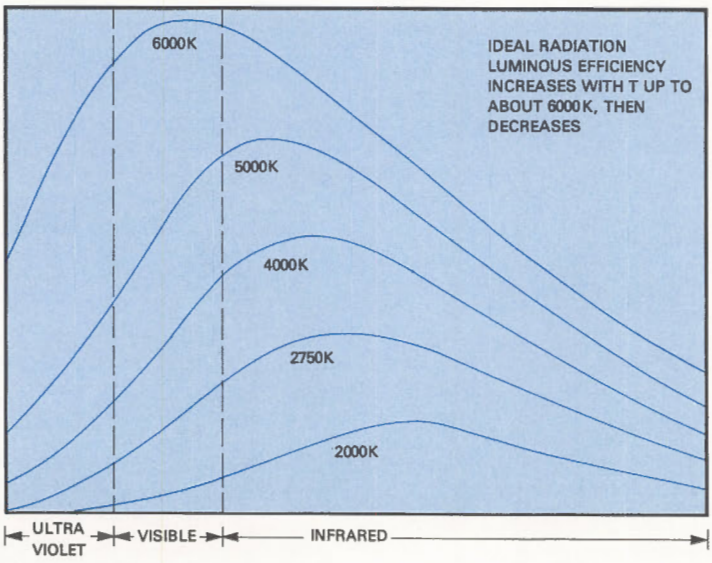


Figure 9.6-2 Spectral radiance curves of blackbodies at various temperatures.

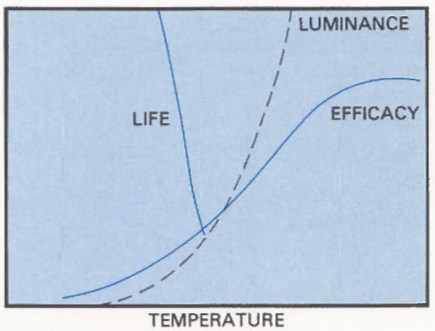


Figure 9.6-5 Life, luminance, and efficacy of tungsten vs. temperature. (Schematic)

Figure 9.6-5 shows how the life, luminance, and efficacy of tungsten-filament incandescent lamps vary with temperature. Luminance and efficacy both increase with temperature while life rapidly decreases with temperature (because of increasing filament evaporation), fall-

ing to zero at about 3655K (the melting point of tungsten) long before efficacy reaches its theoretical maximum (at about 6000K, as shown in Figure 9.6-2). Therefore, for any practical tungsten-filament lamp, efficiency and life are inversely related, as shown in Figure 9.6-6. The corresponding curve for tungsten-halogen lamps has the same general shape as that for non-halogen lamps, but is displaced upward. Thus tungsten-halogen lamps have higher efficacy at the same life as non-halogen lamps, or longer life at the same efficacy as non-halogen lamps. These characteristics of tungsten-halogen lamps derive from the halogen cycle and the high gas fill pressure, both of which retard filament evaporation.

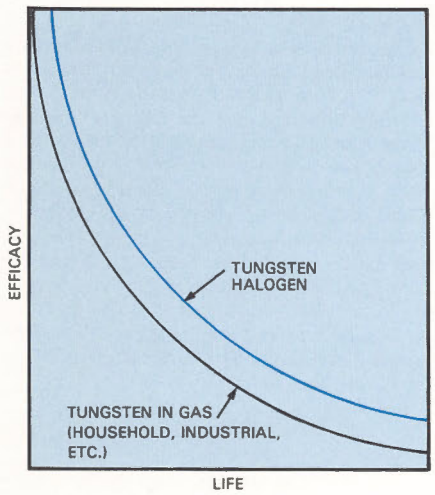


Figure 9.6-6 Efficacy vs. life for tungsten and tungsten-halogen lamps. (schematic)

Figure 9.6-7 shows the distribution of input power in incandescent lamps. Note that only about 6.5% of the input power appears as light, and that about 81% appears as infrared radiation.

In general, for all types of continuous-spectrum incandescent solid emitters, life is limited by evaporation and/or melting, and efficacy is limited from about 50% to about 200% that of blackbodies at the same temperature.

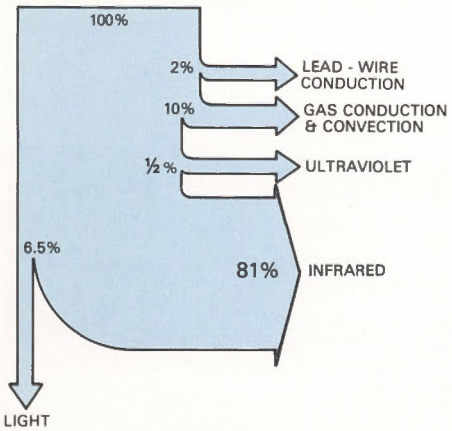


Figure 9.6-7 Distribution of input power in typical incandescent lamp.

Emitters having efficacies greater than those of blackbodies at the same temperatures are somewhat spectrally selective radiators which have higher emittance in the visible than in the infrared.

Discharge Lamps

Discharge lamps operate by the passage of electric current through gases, which can be heated to much higher temperatures (e.g., 6000K) than the melting point of any solid with consequently high spectral radiance in the visible. The gas can be selected to have high radiant emittance only at desired wavelengths (corresponding to transitions of its atoms and molecules), and low radiant emittance at all other wavelengths, especially in the infrared. Also, gases have much lower heat conductivity than solids. These factors permit high luminance, low emission of non-visible radiation, and low heat-conduction losses to supports and walls, resulting in high conversion efficiency of electrical power input to radiation at desired wavelengths. In general, discharge lamps are not limited by the inverse efficacy vs. life curves which are characteristic of continuous-spectrum incandescent solid radiators so that discharge lamps can have lives that are almost completely independent of their luminous efficacy. The factors that limit life of discharge lamps are failure of electrodes to continue to emit or some material failure, such as in the envelope or the seals.

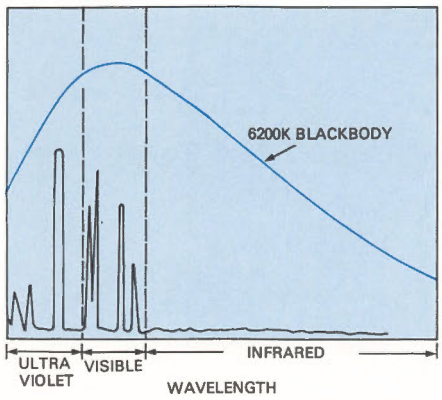


Figure 9.6-8 Comparison of mercury discharge lamp SPD with 6200K blackbody.

Mercury discharge lamps have temperatures of about 6200K at the axis of the discharge. As shown in Figure 9.6-8 (which compares the output of the mercury lamp with that of a 6200K blackbody) the radiant emittance is high at the various spectral lines of mercury in the visible (yellow, green, blue, and violet) and ultraviolet, and almost negligible in the infrared. This compares quite favorably with tungsten-filament lamps, which are limited to operation at much lower temperatures, and which have most of their output in the infrared. Mercury discharge lamps have efficacies of 50-60 lm/W. As shown in Figure 9.6-9, about 16% of the input power is converted to light, about 24% is radiated in the ultraviolet, and only about 10% is radiated in the infrared.

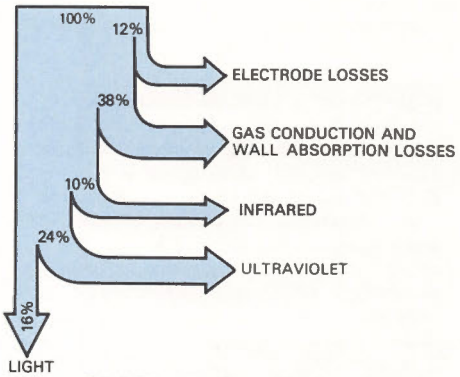


Figure 9.6-9 Distribution of input power in mercury discharge lamps.

Metal-halide discharge lamps employ mercury vapor with various halide additives (e.g., scandium iodide, sodium iodide), and operate at about 5900K-6000K. As shown in Figure 9.6-10 (which compares the spectral output of a metal-halide lamp with that of 6000K blackbody), the metal halide lamp has many spectral lines in the visible in addition to those of the mercury. The efficacy of the Metalarc lamp is about 80 lm/W and that of the Super Metalarc is about 100 lm/W. These lamps have fair color rendering capabilities and can be used wherever cool white fluorescent are acceptable. Figure 9.6-11 shows that 31% of the input power becomes light, 19% becomes ultraviolet, and 17% becomes infrared.

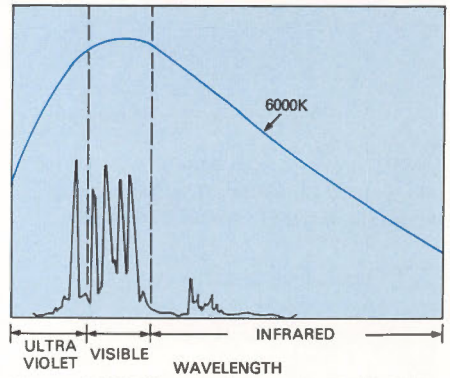


Figure 9.6-10 Comparison of metal-halide lamp SPD with that of a 6000K blackbody.

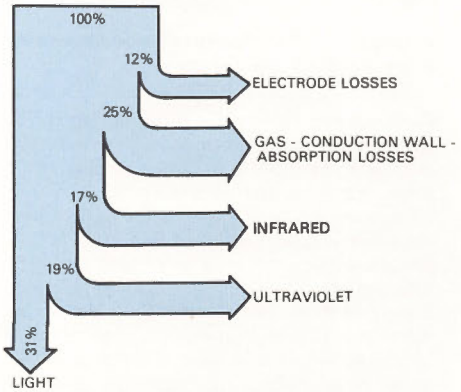


Figure 9.6-11 Distribution of input power in metal-halide lamps.

High-Pressure sodium lamps operate at about 4000K, but the spectral emittance of the lines in the visible is quite high. The spectral power distribution of a typical HPS lamp is shown in Figure 9.6-12 along with that of a 4000K blackbody. The efficacy of 400W HPS lamps is about 100-125 lm/W. Figure 9.6-13 shows that about 27% of the input power becomes light, and about 32% becomes infrared radiation.

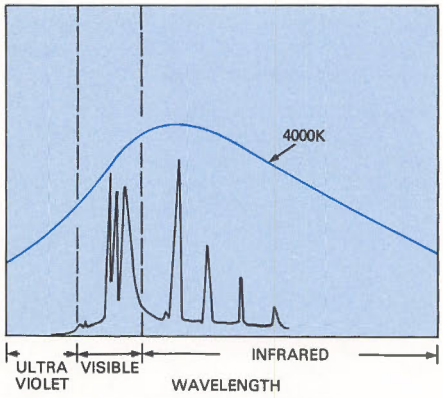


Figure 9.6-12 SPDs of a high-pressure sodium lamp and a 4000K blackbody.

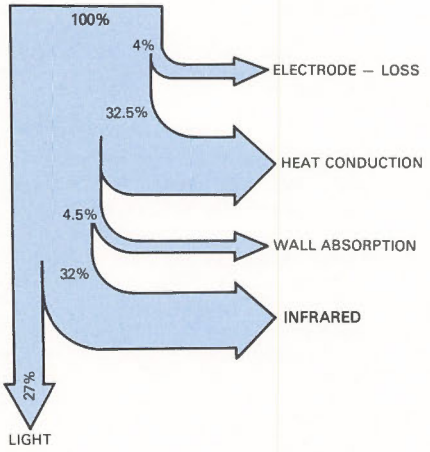


Figure 9.6-13 Distribution of input power in high-pressure sodium lamps.

Fluorescent lamps are different from HID lamps in that the gas pressure is very low (mercury at about 0.001 atm, argon at about 0.03 atm), so that the electrons in the discharge can be accelerated by the electrodes to very high velocities and temperatures (about 11,600K). Since the electrons make only elastic collisions with the gas atoms they do not lose very much energy to those gas atoms which (along with the tube wall) remain at a very low temperature (about 40°C). This is quite different from HID lamps which have much higher gas pressures and in which the temperatures of the electrons and the gas atoms are therefore approximately equal.

Because the mercury pressure in the fluorescent lamp is so low, the principal line is the strong 253.7 line in the ultraviolet. This is shown in Figure 9.6-14, which compares the spectral power distribution of the mercury discharge with that of an 11,600K blackbody. When the 253.7nm mercury line excites the phosphor on the wall, the spectral radiance of the phosphor

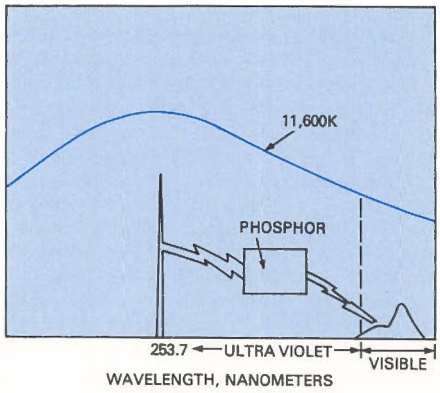


Figure 9.6-14 SPDs of fluorescent lamps and 11,600K blackbody.

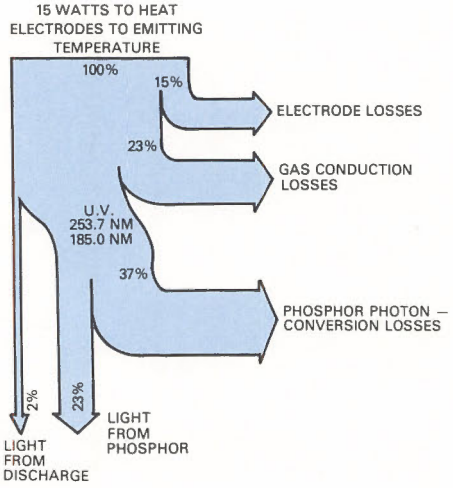


Figure 9.6-15 Distribution of input power in fluorescent lamps.

is much greater than that of a blackbody at the 40°C wall temperature. Although this paradoxically seems to violate the original premise of this section, it does not really do so, because the temperature which limits the radiation characteristics is not the wall temperature but the electron temperature. Fluorescent lamps have efficacies in the order of 80 lm/W. Figure 9.6-15 shows that about 25% of the input becomes light, and about 37% is radiated as ultraviolet.

Cost Comparisons for Various Types of Lamps

Figure 9.6-16 compares four different costs for the various types of lamps which have been discussed. Incandescent lamps have the lowest cost per lumen, fluorescent lamps have the lowest cost per thousand lumen-hours, and high-pressure sodium lamps (which are the most expensive lamps per lumen of all those listed) have both the lowest operating cost per thousand lumen-hours and the lowest life cycle cost per thousand lumen-hours. Note that the tabulated costs include lamp costs and operating costs but exclude costs of fixtures, ballasts, etc. Ballast cost and power loss will slightly increase operating and life cycle costs of all discharge type lamps.

TYPE OF SOURCE	LAMP COST ¢PER LM	LAMP COST– ¢PER 10^3 LM • HR	OPERATING COST– ¢PER 10^3 LM • HR	LIFE CYCLE COST– ¢PER 10^3 LM • HR
INCANDESCENT	.056	.075	.316	.391
TUNGSTEN-HALOGEN	.187	.094	.233	.326
FLUORESCENT	.090	.0038	.072	.076
MERCURY	.124	.0052	.100	.105
METALARC	.191	.0096	.078	.088
HIGH PRESSURE SODIUM	.151	.0063	.044	.051

Figure 9.6-16 Comparative costs of light for various types of lamps, including lamp costs and operating costs, but excluding costs of fixtures, ballasts, etc. Chart is based on popular lamp types and list prices in 1980; relative ranking should not vary as lamp and energy cost change.

10.1 Photographic Applications

The primary function of light in photography is to produce a latent image in a photosensitive material which then can be developed to form a permanent image through appropriate processing. From a design standpoint, this means that the quality and the quantity of the light both must meet the requirements of the photosensitive material in order to produce an optimum image.

Quality of Light

Depending on the spectral sensitivity of a given photosensitive material, some sources will be more efficient than others in exposing the material. Examples of commonly used photographic films and plates include: blue-sensitive; orthochromatic (sensitive to all colors except orange and red); panchromatic (sensitive to all colors); color; and infrared-sensitive. Illustrations of spectral sensitivity curves for some common emulsions appear in Figure 10.1-1.

When selecting light sources for photographic applications, the designer must ascertain that the spectral distribution of the light from the lamp is matched or 'balanced' to the spectral sensitivity of the film in accordance with applicable criteria and that the quantity of radiation in the active spectral regions is adequate for proper exposure. Even in black-and-white materials, color balancing is important for rendering color into gray tones. Color films are so greatly affected by light-source color imbalances that some means of correction often is necessary. This may be accomplished for some light sources by comparing the source color temperature to the color temperature for which the film is nominally balanced and then selecting a filter based on the difference between the two color temperatures.

Color Temperature

Color temperature refers to the visual appearance of a light source and does not necessarily describe its photographic effect. Simply described, the color temperature of a light source is the temperature of a blackbody radiator, the color of which most closely visually matches the color of that source. If an exact match is not possible, then the closest possible match is obtained, and the term 'correlated color temperature' is used. Thus, the color temperature of a light does not describe its spectral composition; it only describes its visual appearance.

Color-temperature balances for photographic systems are based upon sources with spectral distributions similar to those of blackbody sources, e.g., incandescent lamps and daylight. It is only for such sources that selection of films and filters can be based upon color temperature.

When the spectral distribution of the radiation from a light source varies appreciably from that of a blackbody over the wavelengths in which the film is sensitive, color temperature is usually inadequate for determining color balance. For instance, most color films are sensitive to ultraviolet wavelengths, but the eye is not. Without a correction filter, the presence of UV radiation in the scene would render the scene overly blue. Figure 10.1-2 graphically shows the difference in spectral characteristics between two sources of equal color temperature. A typical color film sensitivity curve is plotted to suggest why the color rendition may be affected.

In practice, the discontinuities and departure from monotonic variation with wavelength of the spectral power distribution of many fluorescent and HID lamps make it difficult to balance films to such lamps. Furthermore, it is impossible to balance a film to a source if the source is devoid of radiation in significant spectral regions. This is because color-balancing filters simply attenuate part of the spectrum to bring those regions into balance with the regions of least photographic effect. For example, clear mercury HID lamps (see Figure 10.1-3) have no significant radiation above 590nm. Consequently, there is no way to filter the light from those lamps so as to excite the red film response shown in Figure 10.1-2.

For approximations where color temperature is appropriate, the mired nomograph of Figure 10.1-4 can be used to determine the required filter conversion. The 'mired' (micro-reciprocal-degree) value is defined as follows:

$$\text{mired value} = \frac{1{,}000{,}000}{\text{color temperature (kelvins)}} \qquad \text{(eq. 10.1-1)}$$

For blackbody-type sources, the mired shifts are linearly additive. The difference in mired value between the light source and the film color balance represents the mired shift required of the filter. This is most easily accomplished by the nomograph of Figure 10.1-4. A positive value results when the color temperature is lowered, and a negative value results when the color temperature is raised. Note that the mired nomograph can only be used for filter selection when the light source has a spectral distribution close to that of a blackbody. Figures 10.1-5 and 10.1-6 list some filters and their respective mired shift values.

As stated before, proper exposure depends not only on the quality of the light used but also

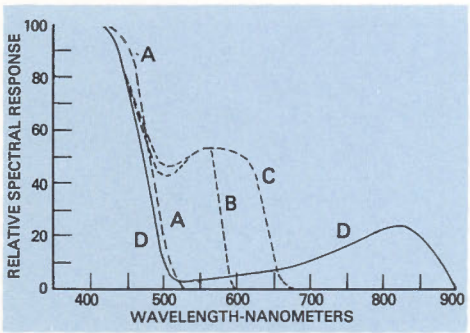


Figure 10.1-1 Spectral responses of common photographic materials. A - blue-sensitive; B - orthochromatic; C - panchromatic; D - infrared-sensitive.

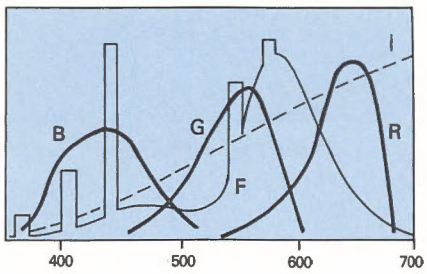


Figure 10.1-2 Average color film response (ANSI PH 3.37-1969) using a typical lens (ANSI PH 2.3-1972), shown as R, G, and B. I is the relative spectral power distribution of a 3050K incandescent lamp, and F is the relative spectral power distribution of a 3050K fluorescent lamp.

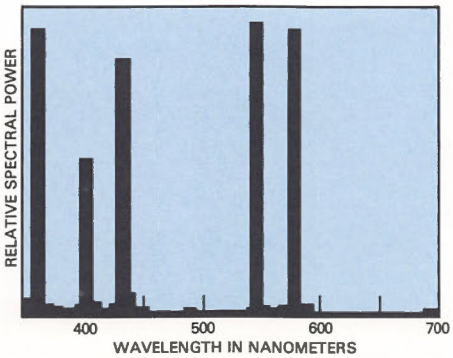


Figure 10.1-3 Relative spectral power distribution of a typical clear mercury discharge lamp.

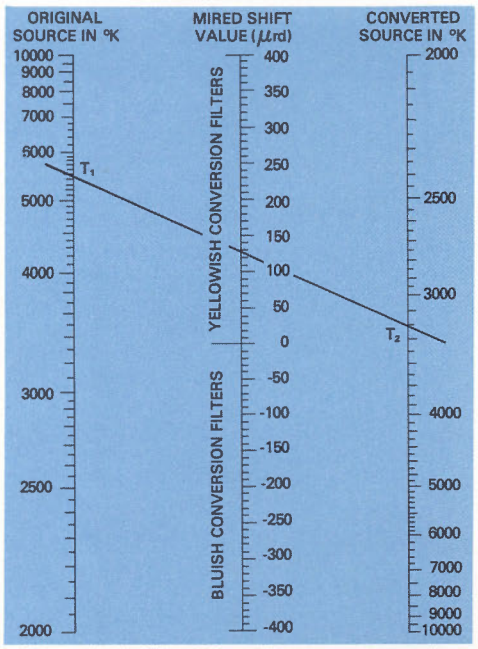


Figure 10.1-4 The Mired Nomograph can be used to find the filter required for a particular conversion by placing a straight-edge from an original source (T_1) to a second source (T_2) as illustrated by the diagonal line. In the illustration, a correction of + 130 mired is required. Certain photographic filters are identified by the mired shift they produce.

on the quantity of light available. Photographic exposure is the product of illuminance at the film plane with time; this is known as the reciprocity law. This law can fail under certain conditions, but for most pictorial films used in average situations, it holds fairly well. The factors affecting the quantity of light that a film receives through a lens are: (1) luminance (brightness) of the subject, (2) exposure time, and (3) lens aperture and transmittance.

The luminance of an object directly affects the exposure of photographic films and TV camera pickups. The luminance **L** of an object having diffuse reflectance **R** is related to the illumination **E** incident on the object by the relation:

$$\mathbf{L} = \frac{1}{\pi}\ (\mathbf{R} \bullet \mathbf{E}) \qquad \text{(eq. 10.1-2)}$$

If **E** is expressed in lm/ft² (fc), then **L** is in cd/ft²; if **E** is expressed in lm/m² (lux), then **L** is in cd/m². Thus, if a diffusely reflecting object of 75% reflectance is placed on a table where the incident illumination is 100 footcandles, the object will have a luminance of 24 candelas per square foot. Equation 10.1-2 is strictly true only for perfectly diffuse (lambertian) surfaces. This equation is sometimes written as $\mathbf{L} = \mathbf{R} \bullet \mathbf{E}$ which requires the obsolete unit of the footlambert for **L** when **E** is expressed in footcandles.

In order to determine the amount of exposure needed for photographic and motion picture work, the reciprocity law is used, and camera and film factors are taken into account. The following equation from ANSI Standard PH 3.49-1971 (for daylight) is used to determine exposure:

$$t_e = \frac{k\,N^2}{LST}\ \text{, where} \qquad \text{(eq. 10.1-3)}$$

t_e = exposure time, seconds

N = f-number (geometric)
L = field luminance, cd/m²
S = ASA film speed (arithmetic)
T = lens transmittance
k = exposure constant (14.2 for 8mm films and 11.4 for larger films.)

Equation 10.1-3 is the basis of exposure meters, whether built into the camera or handheld. The meter measures the overall luminance of the scene and takes the constant and the average lens transmittance factors into account. These meters have a provision for setting the film speed, and the readout is a series of shutter-speed lens-aperture combinations, one of which can be used for the particular scene.

Exposure meters are frequently calibrated for an average lens transmittance of 0.90. Incident light meters are calibrated in terms of the equation;

$$t_e = \frac{N^2\,C}{ES}\ \text{, where} \qquad \text{(eq. 10.1-4)}$$

E = illuminance in lm/ft²
C = exposure constant, 30 ± 5

The f-number of most photographic lenses is designated for an object at infinity; it is defined as the ratio of the focal length to the diameter of the entrance pupil (the clear aperture as seen when viewing the lens in the same direction as the incoming light.) The aperture markings of such a lens are only valid for distance objects, i.e., object distances large with respect to the lens focal length. Equations 10.1-3 and 10.1-4 apply to this situation. Stated another way, the magnification **M** is small compared to unity, i.e., $\mathbf{M} \ll 1$.

In closeup photography, the above-stated condition is not met. The object distance is not large with respect to the lens focal length; the magnification is not negligible compared to unity. In such cases, equations 10.1-3 and 10.1-4 are not correct. The time calculated by these equations must be increased by the factor $(\mathbf{M} + 1)^2$. Stated another way, the geometric f-number (**N**) must be replaced in equations 10.1-3 and 10.1-4 by an equivalent f-number $\mathbf{N_{eq}}$ which is determined from the nominal geometric f-number of the lens by:

$$\mathbf{N_{eq}} = \mathbf{N}(\mathbf{M} + 1) \qquad \text{(eq. 10.1-5)}$$

The standard series of f-numbers appear as 'whole stops' which vary as the square root of two. These whole stops may be subdivided into half-stops as shown in Figure 10.1-7.

FILTER COLOR	FILTER NUMBER	EXPOSURE INCREASE IN STOPS*	CONVERSION IN DEGREES K	MIRED SHIFT VALUE
BLUE	80A	2	3200 TO 5500	−131
	80B	1⅔	3400 TO 5500	−112
	80C	1	3800 TO 5500	−81
	80D	⅓	4200 TO 5500	−56
AMBER	85C	⅓	5500 TO 3800	81
	85	⅔	5500 TO 3400	112
	85N3	1⅔	5500 TO 3400	112
	85N6	2⅔	5500 TO 3400	112
	85N9	3⅔	5500 TO 3400	112
	85B	⅔	5500 TO 3200	131
	85BN3	1⅔	5500 TO 3200	131
	85BN6	2⅔	5500 TO 3200	131

*THESE VALUES ARE APPROXIMATE. FOR CRITICAL WORK, THEY SHOULD BE CHECKED BY PRACTICAL TEST, ESPECIALLY IF MORE THAN ONE FILTER IS USED.

Figure 10.1-5 Conversion filters for color films.

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FILTER COLOR	FILTER NUMBER	EXPOSURE INCREASE IN STOPS*	TO OBTAIN 3200K FROM:	TO OBTAIN 3400K FROM:	MIRED SHIFT VALUE
BLUISH	82C + 82C	1⅓	2490 K	2610 K	−89
	82C + 82B	1⅓	2570 K	2700 K	−77
	82C + 82A	1	2650 K	2780 K	−65
	82C + 82	1	2720 K	2870 K	−55
	82C	⅔	2800 K	2950 K	−45
	82B	⅔	2900 K	3060 K	−32
	82A	⅓	3000 K	3180 K	−21
	82	⅓	3100 K	3290 K	−10
NO FILTER NECESSARY			3200 K	3400 K	—
YELLOWISH	81	⅓	3300 K	3510 K	9
	81A	⅓	3400 K	3630 K	18
	81B	⅓	3500 K	3740 K	27
	81C	⅓	3600 K	3850 K	35
	81D	⅔	3700 K	3970 K	42
	81EF	⅔	3850 K	4140 K	52

*THESE VALUES ARE APPROXIMATE. FOR CRITICAL WORK, THEY SHOULD BE CHECKED BY PRACTICAL TEST, ESPECIALLY IF MORE THAN ONE FILTER IS USED.

Figure 10.1-6 Wratten light-balancing filters.

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WHOLE STOP	HALF STOP
0.7	
	0.84
1.0	
	1.2
1.4	
	1.7
2.0	
	2.4
2.8	
	3.1
4	
	4.8
5.6	
	6.7
8	
	9.5
11	
	13.4
16	
	19
22	
	27
32	
	38
45	
	51
64	
	76
90	
	108
128	

Figure 10.1-7 Standard f-number intervals.

T-numbers, sometimes used on motion picture cameras, take both the (geometric) f-number and lens transmittance into account, as follows:

$$T\text{- number} = N/\sqrt{T} \qquad \text{(eq. 10.1-6)}$$

Flash Photography

Flash photography has become popular as a simple and convenient way to obtain high light levels balancing shadow levels in daylight as well as for night-time and indoor photography. The short durations (typically less than a millisecond) inherent in electronic flash units have also made it possible to capture moving people and objects with clarity. Stroboscopic and high-speed camera systems are based upon electronic flash.

The faster films and faster lenses of recent years together with automatic exposure control have reduced the absolute necessity of flash to obtain a picture in amateur photography. However, flash on such cameras insures that exposure times do not become excessive when light levels are low. More important, available light frequently will produce excessive contrast, and a flash unit on the camera can be used to fill in shadows in such situations.

Chemical Flash Photography

Disposable chemical flashbulbs, or photoflash bulbs, rely on a chemical reaction to produce light, namely, the rapid combustion of a metallic foil. Section 2.3 describes the properties and types of flashbulbs.

Synchronization delay for flashbulbs depends on the interrelation between the camera and shutter, the lamp type, and the intended service. Amateur cameras usually use flash exposure settings up to 1/60 of a second and require flash delays on the order of 10msec. Slower shutter speeds utilize a larger fraction of the flashlamp output.

Flashlamps for professional service have delays nearer 20msec for compatibility with leaf shutters used at higher speeds. Timing becomes more important with higher shutter speeds.

Focal-plane shutters use FP type lamps which are designed to burn longer with a plateau of near-constant peak output. This is necessary due to the scanning action of the two curtains which make up the focal-plane shutter. The effective slit width depends on the shutter speed selected, becoming increasingly narrow with faster speeds. Travel time of these shutters is usually between 15 and 45msec. Thus, only the longer-burning FP type of flashlamp results in even illumination at the film plane. Shutter delays are 10 to 15 msec after shutter release.

Xenon ('Electronic') Flash Photography

The xenon flashtube is an arc discharge lamp that converts electric energy into intense light energy of short duration. It consists of a transparent tube filled with xenon gas and is available in a variety of straight and coiled configurations for use in what is commonly called 'electronic flash' photography. Some types come with an outer envelope which acts as a safety device, a diffuser, and/or a filter to modify the spectral distribution of the light. The spectral distribution of the xenon flashtube is similar to that of daylight at about 6000K and extends sufficiently into the ultraviolet and infrared to be useful for special applications. Section 6.1 describes the various characteristics of these lamps.

High-energy lamps with ratings from several hundred to several thousand joules are used in applications such as studio, large area outdoor, and aerial photography. Medium-energy lamps from about 50 to about 200 joules are used for general photography by both professional and amateur photographers. Low-energy lamps with the ratings in the order of tens of joules are used in amateur cameras with fast film and fast lenses primarily as fill or supplementary light to available light. Special lamp and circuit combinations provide short-duration flashes, in the order of microseconds, for high-speed stop-action photography.

Xenon flashtubes are invariably mounted in reflectors to concentrate the light on a subject. Units for small amateur cameras frequently have a trough-shaped reflector with a linear tube. These designs are compact, but the efficiency is low since light control is principally in the plane perpendicular to the lamp. Larger amateur and professional type units often use compact helical lamps with reflectors that control the beam shape in both the horizontal and vertical planes. Such systems can be made quite efficient. However, the beam spread is usually designed to be somewhat larger than the camera field of view since precise alignment between the two is difficult.

Synchronization for electronic flash photography requires that the flash be fired as soon as the shutter is fully open because xenon flashtubes produce their peak light almost instantaneously and the rise time can usually be considered negligible. In cameras with diaphragm type shutters, 'X sync' designation means that the flash contacts will close when the shutter is fully open. Also, since the flash duration is generally less than a millisecond, any shutter speed up to the fastest may be used successfully.

Focal-plane shutters can only be synchronized with electronic flash up to 1/60 or 1/125 second due to the short durations of these flash units and the shutter scanning action. The limiting value is the fastest shutter speed at which the entire shutter remains open during the flash. At higher speeds, only part of the negative area will be exposed. This can be observed visually by looking through the back of a camera pointed at the flashlamp at the instant the shutter is tripped. Incorrect shutter synchronization will show a partially closed aperture.

Application of Xenon Flashtubes

The flash duration is determined by the circuit, not by the lamp alone. Energy rating of the lamp in watt-seconds (joules) is a reliable indicator of the total light output of the lamp. Photographic flash lamps generally operate at a conversion efficiency of 30-50 lumen-seconds per watt-second. The energy rating of a lamp is the upper limit of operation to avoid premature lamp failure. To determine the actual photographically effective light, it is necessary to take into account the effect of the reflector and the relation of the flash unit to the photographic subject.

The power rating of a lamp in watts is also of significance since this sets an upper limit on the rate at which lamps can be repetitively flashed without causing lamp failure. The maximum number of flashes per second for more than a few flashes is given by:

$$N = P/E \qquad \text{, where} \qquad \text{(eq. 10.1-7)}$$

P is the power rating in watts and **E** is the energy rating in watt-seconds. In an actual flash system, the maximum flash rate is limited by the charging time of the energy storage capacitor.

Exposure by xenon flash can be characterized by guide numbers in a manner analogous to that used for photoflash (see Section 2.3). Due to the short duration of the flash, all of the generated light is photographically effective.

The guide number equation for electronic flash, repeated from Section 6.1, is:

$$GN = \sqrt{0.005 \times M \times S \times Q \times (L/W)}$$

, where (eq. 10.1-8)

GN = guide number
M = reflector factor
S = ASA film speed (arithmetic)
Q = flash energy, watt-seconds (joules)
L/W = lamp efficiency, (lm-sec)/(watt-sec)

The guide number is the product of the lens f-number with the lamp-to-subject distance in feet. When this factor has been determined for a flash unit, the photographer can rapidly set his exposure for a given subject.

A typical reflector factor for xenon flashlamps would be in the range of 6-8. The value ranges from about 3 for wide beam patterns to about 15 for narrow beam patterns. Using a reflector factor of 7 and a typical efficiency of 35 lm-sec/watt-sec, the graph of Figure 10.1-8 gives the approximate guide numbers for common flash units.

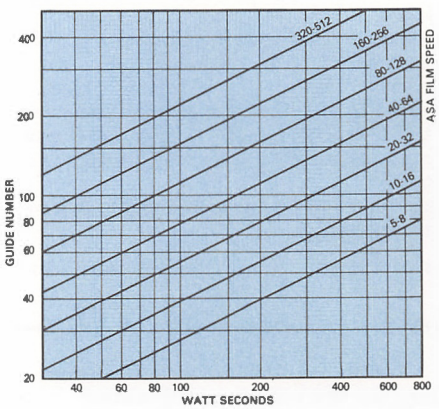


Figure 10.1-8 Guide numbers for typical xenon flash units.

Photographic Lenses

Camera lenses have at least one antireflection coating, and high-efficiency multilayer coatings are becoming increasingly popular in modern lenses. These coatings reduce reflection losses incurred when light is incident on an air-glass interface, as seen in Figure 10.1-9.

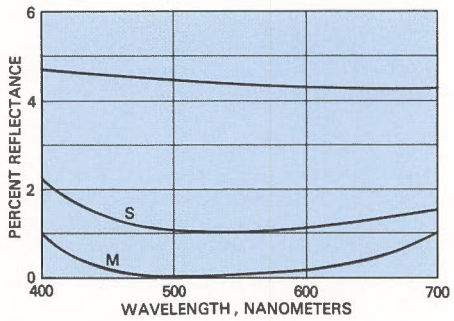


Figure 10.1-9 Spectral reflectance of single layer (S) and multilayer (M) anti-reflection coatings compared with uncoated glass surface; n = 1.517.

Reflection loss of 4 ½ % for a typical uncoated optical glass can be reduced to 1 ½ % by a single layer coating; a multilayer coating further reduces this to less than ½ %. Uncoated glass increases the possibility of stray light problems so that a camera pointed in the direction of a light source may have ghost images, reduced contrast, and flare spots. Even if the light source is not visible in the viewfinder, overall reduction in contrast can occur if all or part of the lens is not shielded from the light.

Photographic lenses have always shown variations in the color of light they transmit. This is caused by the type and thickness of the glass used as well as the spectral transmittance of the coating applied to lens. Due to optical design factors, the lens thickness and type of glass cannot easily be varied to produce a desired color, while coatings can be made having different tints to optimize the overall color of the lens systems. The ANSI photographic standard PH 3.37-1969 has defined a 'color contribution' for lenses used in pictorial color photography. This is a three-number designation representing the effective densities of the blue, green, and red components of the lens. The lowest density is made equal to zero, and the results are multiplied by 100. The recommended color contribution for photographic lenses is 7-0-0, meaning that the typical lens should have an overall blue density of 0.07. Photographic density is defined as minus the logarithm of the sample transmittance:

$$\mathbf{D} = -\log_{10} \mathbf{T} \qquad \text{(eq. 10.1-9)}$$

Film and Television System Requirements

The relationship of film speed (ASA number), lens aperture, and exposure time establishes the light requirements for film. Light levels in footcandles required for ASA 160 film are listed in Figure 10.1-10.

In the case of color television cameras, the signal-to-noise ratio (S/N) for the camera establishes a minimum illumination level. For many modern color television cameras, a 40dB signal-to-noise ratio is needed for acceptable picture quality. Typical illumination levels required at various lens apertures by such color television cameras are listed in Figure 10.1-11.

Early color television cameras needed a higher signal-to-noise ratio to overcome the problem of color lag, which required about 1/3 more illumination than the values listed in Figure 10.1-11. Future camera developments will probably allow a decrease in the required illumination. The use of zoom lenses doubles the required value of illumination. Lens extenders used for many remote pickups where distances are great also double the necessary light level. Thus a remote pickup would require at least 75 footcandles using an f/2 lens, and, if a 2X lens extender were added, 150 footcandles would be needed.

There are a variety of black and white television camera types available to meet almost every application need. Any system can obtain pictures in sunlight, but Figure 10.1-12 gives an indication of the generally accepted and the minimum light levels for pictures from various types of systems.

Studio Lighting

To the photographer, lighting a subject in the studio is one of the most difficult parts of the job because the possibilities are endless and limited only by the imagination. Aside from providing a level of illumination compatible with a particular film, lighting can develop mood, enhance composition and subject depth, recreate natural light sources such as sun or fire light, etc. Where the primary consideration is to create a natural outdoor lighting effect, i.e., the simulation of outdoor conditions inside the studio, his task is accomplished by keeping the main light above and at an angle to the subject and by producing only one set of shadows, as the sun would naturally do. In practice, the photographer first establishes the main light for overall subject illumination. Highlights are then added to give the object shape and perhaps emphasis. Finally, a fill-in light is placed to provide adequate shadow detail rendering for the film. Usually, a highlight-shadow ratio of 3:1 or 4:1 is adequate for most pictorial films.

Luminaires

The Illuminating Engineering Society defines a luminaire to be a complete lighting unit consisting of a lamp or lamps together with the parts designed to distribute the light, to position and protect the lamps, and to connect the lamps to the power supply. Luminaires are roughly categorized as being of a flood or spot design, but these are not uniquely distinct. Each luminaire has properties which characterize its operation. These include beam distribution, evenness of field, luminaire size, barn-door action, shadow properties, sharpness of beam edge, etc.

EXPOSURE TIME, SEC.	LENS APERTURE (F / NUMBER)				
	F/2	F/2.8	F4	F/5.6	F/8
1/50	30	60	120	240	480
1/100	60	120	240	480	960

Figure 10.1-10 Illumination in footcandles required for ASA 160 film at various shutter speeds and lens apertures.

LENS APERTURE (F/NO.)	F/2	F/2.8	F/4	F/5.6	F/8
ILLUMINATION (FC)	37.5	75	150	300	600

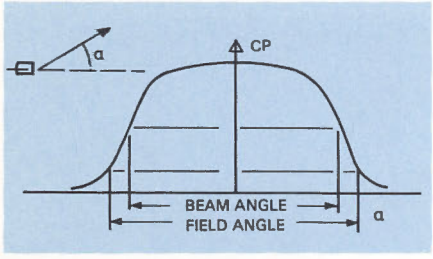
Figure 10.1-11 Illumination levels required at various lens apertures by modern color television cameras.

CAMERA SYSTEMS	ILLUMINATION LEVELS — FC	
	GENERALLY ACCEPTED	MINIMUM
VIDICON	100	5
SILICON DIODE ARRAY	10	0.5
INTENSIFIED VIDICON	2	0.1
SILICON INTENSIFIED TARGET	0.2	0.01
INTENSIFIED SILICON INTENSIFIED TARGET	0.01	0.0005

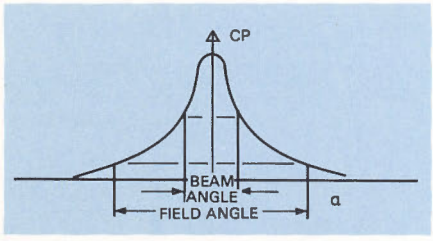
Figure 10.1-12 Typical light levels required for various television camera systems.

Beam characteristics for a luminaire are simply characterized in terms of beam angle (50% intensity points), field angle (10% intensity points), and central intensity. A complete description of the beam requires that the beam intensity be plotted as a function of position in the beam. If the beam is nominally symmetrical about the centerline, which is the common case for photographic luminaires, the intensity can be plotted as a function of angle from the centerline. If the beam is not circularly symmetric, then intensity plots in different directions must be used to describe the entire beam. The intensity plots may be on either rectangular or polar coordinates. Rectangular plots are usually easier to use if values are to be read from them, but polar plots give a graphical interpretation of the beam shape and coverage.

These intensity distributions are useful both for predicting lighting performance and for comparing various luminaires. For example, the difference in beam and field angles for a luminaire is related to overall uniformity and edge quality. If the beam angle and field angle are close as in Figure 10.1-13a, the pattern will tend to be uniform and have a reasonably sharp edge cutoff. If the beam angle is small and the field angle large, as in Figure 10.1-13b, then the intensity pattern will tend to be high in the center and gradually fall off.



a) Field and beam angles of similar size



b) Field angle much larger than beam angle

Figure 10.1-13 Intensity distributions of luminaires.

Beam and field efficiencies of the luminaire are also of importance. The efficiency of a lighting unit is defined as the ratio of the lumen output of the instrument to the lumen output of the lamp. Thus, the beam and field efficiencies refer to the percent of the lamp lumens within the respective angular zones. Depending upon which part of the beam is utilized, one or both of these will be a useful measure for luminaire performance. The beam efficiency is a better measure when evaluating a unit for lighting a single subject centered in the beam. If the beams of several units are partially overlapped, then field efficiency is a useful measure since light clear out to the field angle probably is effective.

The evenness of field is a subjective evaluation of a luminaire. Unevenness is characterized by the appearance of dark rings, bands, or striations when the beam is viewed on a flat wall. Intensity diagrams often will not show these defects since the intensity readings are usually taken at intervals of several degrees, and an average of several directions is commonly shown. Nonuniform regions may be inherent in the design of the luminaire and may be caused by misaligned or damaged components, use of wrong lamps, etc.

The size of a luminaire is important from a shadow-casting standpoint. For instance, a Fresnel spotlight in the spot position will have a softer shadow than in the flood position. This is because in the spot position the entire lens surface acts as a light source; in the flood position the source is close to the lens, and the effective source size is much smaller. Thus, scoop floodlights with their large-diameter reflectors generally produce soft shadows.

Shadows are an important part of lighting design. The designer is interested in many aspects: the darkness in the shadows, the sharpness of the edges, the possibility of multiple shadows due to separate parts of a source such as a C-13 filament, etc. In general, physically large sources have the potential of producing softer shadows, but the shadows obtained depend on the optical control of the light from the luminaire.

Tungsten-halogen lamps can be substituted directly into luminaires designed for conventional lamp use. The efficiency does not increase significantly although the other advantages of tungsten-halogen lamps are realized.

Barn doors on luminaires have two principal purposes; to mask light from a particular part of the scene and/or to shield light from a camera lens. Since barn doors are attached to the luminaire, the source size is not negligible; thus, barn doors do not cast sharp shadows. On some luminaires such as Fresnel lens spotlights, soft but distinct shadows are produced. On many reflector type spotlights, barn doors may not cast distinguishable shadows but will simply cause various parts of the beam to be dark. This is due to the distribution of light from the different parts of the reflector. Barn doors are still used on such luminaires to shield light at large angles from the main part of the beam.

Floodlights of various types such as scoops, broads, and pans are generally large, diffuse reflector luminaires with field angles less than about 120 degrees. These produce efficient (typically 40-60%) and uniform lighting without creating harsh shadows. Some shadow texture control is afforded by the reflector finish which may range from a flat white to a diffuse textured aluminum. These luminaires also have short throws and in general do not barndoor well. Figure 10.1-14 shows typical scoop pattern. Standard incandescent lamps used in these luminaires are frosted to prevent harsh shadows due to direct filament radiation. When tungsten-halogen lamps are used, small masks in front of the lamps eliminate direct radiation. Longer-range scoops combine matte and specular reflector design and allow movement of the lamp to provide limited beam control. The beam angle is generally smaller than the regular scoop and produces a less-soft quality of illumination.

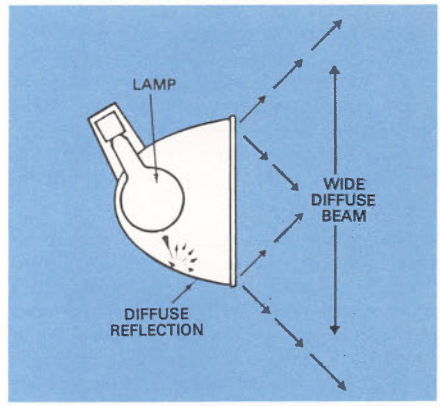


Figure 10.1-14 Scoop floodlight.

Parabolic reflector lamps, or PAR lamps, are popular as floodlights which are small, lightweight, portable, and convenient when precise beam control is not required. These come in a variety of beam spreads ranging from about 25° to 70°, in photographic color temperatures, and in tungsten-halogen and non-halogen types.

Spotlights are characterized by narrower beam angles than floodlights, on the order of 10 to 35 degrees. The overall quality of the illumination tends to be hard in comparison to floodlights.

Ellipsoidal spotlights, as shown in Figure 10.1-15, use an efficient ellipsoidal reflector to collect light from a lamp and direct it through an aperture onto a lens system. The lens system focuses the aperture at a large distance in front of the fixture. Shutters or variable position masks located at the aperture project into the field and can sharply cut off light in varous parts of the beam. Although the shutters could be used to completely vary the beam size, they inefficiently throw away light. Consequently, the basic beam size is varied by changing the lenses to go from wide to narrow beams.

Ellipsoidal spotlights produce shadows which are sharp, well defined, and dense. The size of the light source has relatively little effect on the shadow characteristics. Usually, the central part of the beam is of high intensity with a gradual drop off to the edge of the beam. Center-to-edge ratios as great as 10:1 are not uncommon, and efficiencies are on the order of 30 to 40%.

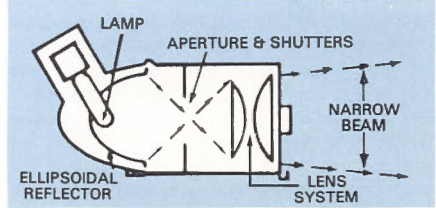


Figure 10.1-15 Ellipsoidal spotlight.

The design of ellipsoidal spotlights is straightforward. The lens diameter sets the maximum possible intensity. The gate diameter, lens focal length, and gate-to-lens spacing are related to the desired 'throw' and beam size.

With a sufficiently large filament in a given luminaire, each point in the aperture sends light to every point in the lens. When this condition is met, inserting a larger wattage lamp cannot appreciably increase the beam intensity, i.e., there is a maximum-size filament for a given fixture. For filaments smaller than this maximum size, intensity will depend on lamp wattage since the lens now is not fully bright. This is shown in Figure 10.1-16.

Beam projectors have parabolic reflectors so than any ray originating at the focal point and incident on the reflector will leave parallel to the reflector axis as shown in Figure 10.1-17. The rays from all points of the filament to a point on the reflector emerge as a narrow cone of rays centered about the ray which originated at the focal point. The intensity **I,** (cd) for this type of luminaire is given by:

$$I = rLA \quad \text{, where} \qquad \text{(eq. 10.1-9)}$$

r = reflectance of the reflector,
L = average luminance of the source (cd/in²),
A = projected area of the reflector (in²).

The only ways to increase the intensity of the light from this luminaire is to increase the luminance (by increasing color temperature and decreasing life for incandescent lamps) or to use a larger-diameter reflector. Increasing the wattage of an incandescent lamp would increase the filament size and therefore spread the beam as shown by the dotted lines in Figure 10.1-17.

Because of the nearly parallel direction of light, this luminaire provides a narrow, high-intensity beam pattern. The beam spread and light pattern are determined by the focal length and diameter of the paraboloidal reflector and by the filament size and shape. Typical intensity distributions are illustrated in Figure 10.1-18.

Fresnel spotlights (Figure 10.1-19) are basically comprised of a Fresnel lens and a moveable light source behind the lens. The Fresnel lens is equivalent to a simple plano-convex lens but is made thin by stepping the convex surface. Advantages of this thinner lens are less weight and a reduced tendency to crack with high temperatures. Some lens aberrations can also be partially corrected, and a controlled amount of diffusion can be added to eliminate projection of filament striations. The lamp is adjustable between the lens and its focal point to vary the size of the beam.

Shadow characteristics for the Fresnel spotlight range from soft and ill-defined in the spot-focus position to dense and somewhat harder in the flood-focus setting. This is because in the spot setting the lens is fully flashed. The bright area which is the effective source size is larger than in the flood setting. As the source is moved from spot to flood setting, it approaches the lens. This reduces the magnification of the source but allows the light to spread through a larger angle. This is also evidenced by the difference in efficiency, which is about 10% in the spot position compared to about 30% in the flood position.

Still and Motion Picture Projection

Projection generally refers to the magnification of an object to form a bright image on a screen for display. In most cases the object is flat and transparent. In this section, we will only consider transparency projection.

Two basic types of illumination are used for transparency projection: Kohler illumination and Abbe illumination. Kohler, or two stage illumination, is shown in Figure 10.1-20. In this system, a condenser lens images the source (e.g., a lamp filament) at the projection lens, and the transparency, located close to the condenser, is imaged onto the screen by the projection lens. The condenser magnifies an image of the filament to just cover the projection lens pupil. If light did not reach all parts of the lens from each point on the transparency, the lens would be working at less than its rated speed. On the other hand, light outside of the pupil is not projected to the screen.

The graph of Figure 10.1-21 shows the screen illumination as lamps of larger and larger wattage are put in a given projector. The sketches above the curve show a view looking into the projection lens from the screen. At **A** the filament is too small to fill the pupil, and screen illumination is low. As lamp wattage increases, the filament size (area) increases, almost proportionally increasing screen illumination.

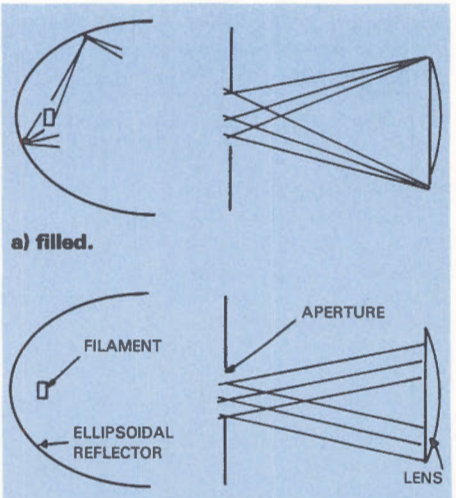


Figure 10.1-16 Rays in an ellipsoidal reflector spotlight.

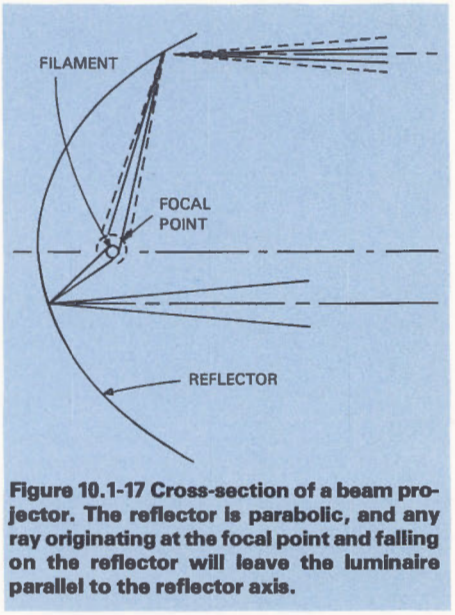


Figure 10.1-17 Cross-section of a beam projector. The reflector is parabolic, and any ray originating at the focal point and falling on the reflector will leave the luminaire parallel to the reflector axis.

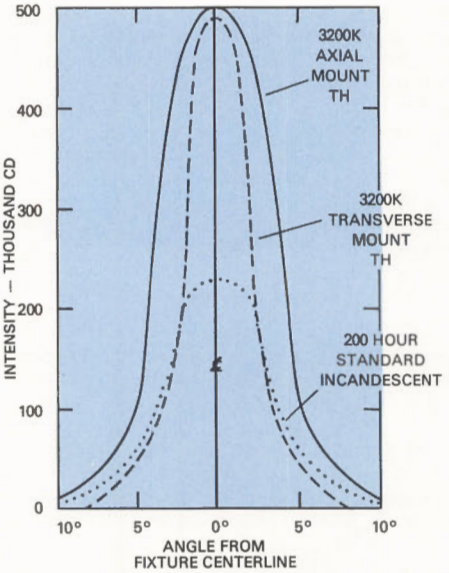


Figure 10.1-18 Intensity distributions of a 16-inch beam projector for three different 1000W lamps.

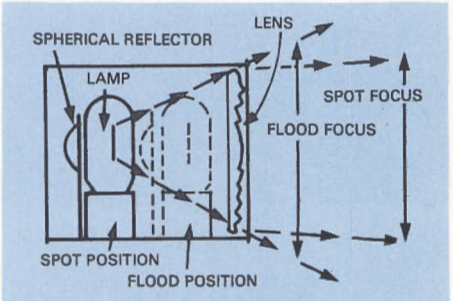


Figure 10.1-19 Fresnel spotlight.

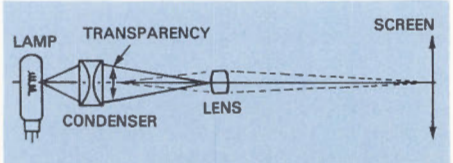


Figure 10.1-20 Transparency projector employing Kohler illumination.

When the filament fills the lens pupil at **B**, screen illumination becomes maximum. A larger filament as at **C** is imaged larger than the projection lens pupil by the condenser. Thus, there is a maximum possible illumination for a given projector. If a projector is designed to operate in the vicinity of **B**, screen illumination can only be increased by changing to a source of greater luminance.

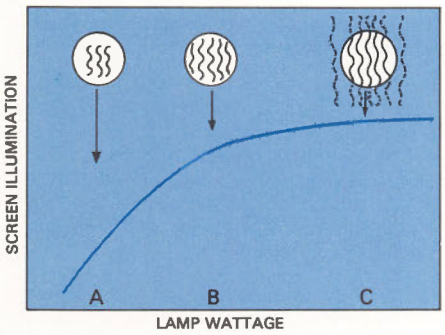


Figure 10.1-21 Screen illumination versus size of lamp filament in a projector employing Kohler illumination.

Abbe illumination is shown in Figure 10.1-22. An ellipsoidal reflector directs light from the source onto the transparency. No image of the source is formed when deep (fast), efficient reflectors are used. Very shallow (slow) reflectors used with arc sources in motion picture projectors tend to form a source image near the transparency, and in such cases, the source must have uniform luminance. Any nonuniformities near the in-focus transparency would be imaged on the screen. The reflector must extend out to the dashed rays, the rays at largest angle from the axis which will pass through both

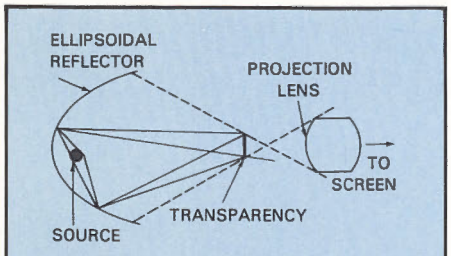


Figure 10.1-22 Transparency projector employing Abbe illumination.

the transparency and the lens.

A deep reflector in an Abbe system is much more efficient than a Kohler system due to the greater collection of light as shown in Figure 10.1-23. The principal effect is to reduce the required lamp wattage and thus the heat in the projector. As a secondary effect, the screen illumination is usually greater in the Abbe system due to reduced attenuation in the condensing system. The Kohler system generally has two or more condensing lenses plus a heat absorbing filter. The net transmittance of these may well be only 60%. The Abbe reflector frequently is a cold mirror, i.e., a reflector which passes infrared to the rear and directs only the light forward. If further filtering is unnecessary, then a single reflectance of about 90% represents the only condenser attenuation.

The Kohler system has an advantage in that filament nonuniformities tend to average out since each point on the source contributes to the illumination of all parts of the screen. In the Abbe system, various points on the source contribute to different parts of the screen. This becomes more severe as the projection lens speed decreases, so that screen uniformity becomes difficult to control unless fast projection lenses are used. The reason for this effect is that the solid angle of light acceptance by the projection lens decreases as the lens becomes slower. As the solid angle becomes less, light is preferentially accepted from a smaller and smaller region of the reflector, and thus the filament is seen from a more restricted range of directions.

The equation determining axial image illumination in a projector system is

$$\mathbf{E} = \frac{\pi \mathbf{T L}}{4\mathbf{N}^2(1+\mathbf{M})^2} \quad \text{, where} \qquad \text{(eq. 10.1-10)}$$

E = image illumination in lm/m²
T = transmission of the optical system
N = f-number of the projection lens
M = image magnification
L = average luminance of the filament in cd/m².

Thus, it is the source luminance and not wattage which determines screen illumination provided that the lens is completely filled or fully flashed, i.e., all parts of the projection lens receive light. Illumination at the center of the screen is generally greater than at the corners due to the cosine-fourth law fall-off, lens vignetting in off-axis directions, etc.

The luminance of the source as seen by an observer looking directly into the projection lens is equal to the actual luminance of the source reduced only by lens transmission factors. Thus, the product **TL** in equation 10.1-10 represents the average source luminance as seen looking back from the screen into the projection lens. Because of interreflections from other parts of the filament coils in incandescent lamps, the luminance of ordinary projection lamps will be somewhat higher than that of a solid tungsten wire, say on an order of magnitude of 2000 cd/cm².

Screen illumination is not a good descriptive parameter for projection systems since it is dependent on screen-to-projector distance. However, total screen lumens are relatively independent of screen distance. Consequently, projectors are commonly rated in terms of

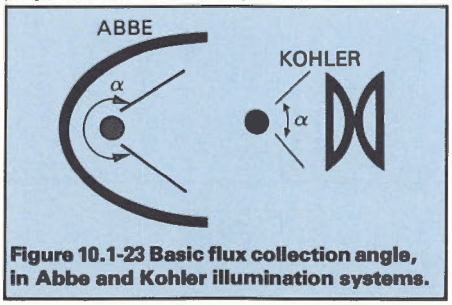


Figure 10.1-23 Basic flux collection angle, in Abbe and Kohler illumination systems.

screen lumens and corner-to-center ratio. Depending upon objectives, just the average corner-to-center ratio may be used, or other values such as the minimum of the four corners may be used also.

Tests of screen lumens are performed with the film gate empty. Motion picture projectors are tested with the shutter stopped in an open position. Some tests may be specified with shutter operating, etc. The most recent ANSI Standards should be consulted, and test conditions should always be explicitly referenced. It is important to remember that, under operating conditions, motion picture screen lumens are significantly reduced (generally about 50%) by the shutter. There are standards established by ANSI for measurement of screen lumens. These specify a selected number of points, typically nine or twelve, at which illumination is measured. The average of these values is multiplied by screen area to determine screen lumens. This abridged, but standardized, technique is simpler than an exact determination of screen lumens.

Condenser Design

The function of the condenser is to properly image the source at the appropriate aperture, as shown previously in Figure 10.1-20. Great precision is not required in the design of the condenser system, and often it can be designed reasonably well on a lens bench or by graphical methods.

System Design

Lenses used for projection should be of good quality since the entire system capability is based on its optical imaging performance. Format, projection distance, and screen size set the focal length of the projection lens. Next, the lens aperture must be established, from which condenser design and source selection follow. Using available projection lenses may prove more economical than designing one for each application.

Projection aperture dimensions are shown in Figure 10.1-24 for common film formats. Figure 10.1-25 relates screen image size and focal length for various formats.

In projection systems, the screen image size can be related to the focal length of the projection lens and the lens-to-screen distance by the equation:

$$\mathbf{D} = \mathbf{F}(\mathbf{M} + 1) \qquad \text{(eq. 10.1-11)}$$

D is the Image distance and **F** is the lens focal length, both expressed in the same units of length. **M** is the magnification, i.e., the ratio of image width (or height) to transparency width (or height). From equation 10.1-11 it is seen that, if the image size is to be increased when projecting at a fixed distance, a shorter focal length lens must be used. Also for a constant image size or magnification, a lens of a longer focal length must be used to project to greater distance. Finally, with a given focal-length lens the image size increases as the projection distance increases.

Heat Control

The temperature of film at the film gate is determined principally by the radiant energy absorbed. Thermal considerations must make

allowance for the densest transparency that can be used. A general goal is to filter non-visible radiation from the light before it reaches the gate, but even absorbed radiation in the visible spectrum represents heat. Film temperature is also affected by ambient conditions at the gate, such as air temperature and long-wavelength radiation from the surrounds.

There are several methods commonly used to control projector heat, both at the film gate and for the entire projector. These include:

a. Forced air cooling; unless care is taken, this may over-cool tungsten-halogen lamps.

b. Infrared absorbing glass in the beam; this generally has appreciable selective absorption in the visible spectrum and reradiates absorbed power as long-wavelength infrared to the immediate surrounds.

c. Hot mirrors in the beam which direct infrared radiation out of the light path.

d. Cold mirrors on the lamp or in the beam to direct the light toward the gate but allow infrared to dissipate in other directions.

e. In certain high power projectors, liquid gate cooling is used.

Tru-Beam Lamps For Condensing Optics

In many projection systems, especially those for small film formats, the lamp serves both as the light source and as the condensing reflector of the Abbe system (see Figure 10.1-22). This lamp, the Tru-Beam lamp, has a tungsten-halogen lamp capsule mounted within a dichroic-coated glass reflector as shown in Figure 10.1-26.

Generally, the reflector is ellipsoidal in shape. The filament is located near the internal focal point, and the light rays are concentrated near the external focal point. The film gate is located near this external focal point. While it is convenient to describe an elliptical reflector contour with its focal points, they have no exact theoretical relation to the projector optics since neither the filament, the film gate, nor the lens are geometric points.

Each Tru-Beam lamp type has been designed to meet the requirements of a particular projection system. To avoid needless proliferation of lamp types, it is desirable to use an existing lamp type for a new projection system providing that a suitable one exists.

In manufacture, the lamp filament is precisely focused within the reflector using an optical device with the properties of the projection system to insure optimum lamp performance. The reflecting surface is a dichroic-coated cold mirror which reflects the visible light while transmitting the infrared filament radiation to the back of the lamp.

Tru-Beam lamps are sometimes used with

FORM	DIMENSIONS (1)	ASPECT RATIO (2)	FORM	DIMENSIONS (1)	ASPECT RATIO (2)
SLIDES			MOTION PICTURE FILM		
135 - 35MM	0.906X1.344 IN	1.48			
135 - HALF FRAME	0.626X0.906 IN	1.44	8MM	0.129X0.172 IN	1.33
126 - INSTAMATIC	26.5X26.5 MM	1.00	SUPER 8	0.158X0.211 IN	1.33
SUPERSLIDE - 127	38. X38. MM	1.00	16MM - STANDARD	0.284X0.380 IN	1.33
SUPERSLIDE - 828	26.2X38. MM	1.45	16MM - ANAMORPHIC	0.284X0.380 IN	2.66
KODACHROME DUPLICATE (3)	30.7X30.7 MM	1.00	35MM - STANDARD (TV)	0.600X0.825 IN	1.33
KODACOLOR TRANSPARENCY (4)	30.7X30.7 MM	1.00	35MM - WIDE SCREEN	0.447X0.825 IN	1.85
110 - 30X30MM SLIDE	0.472X0.622 IN	1.33	35MM - TODD AO (5)	0.715X0.839 IN	2.35
FILM STRIP - 35MM	0.680X0.906 IN	1.33	70MM - SUPER PANAVISION	0.868X1.913 IN	2.21
LANTERN SLIDE - 3¼X4 INCH	2.25 X3.00 IN	1.33	70MM - ULTRA PANAVISION (5)	0.868X1.913 IN	2.35 PLUS

(1) NOMINAL VALUES, REFER TO APPROPRIATE ANSI SPECIFICATIONS FOR EXACT DIMENSIONS.
(2) RATIO PROJECTED WIDTH TO PROJECTED HEIGHT.
(3) FROM 1-5/8 X 1-5/8 INCH TRANSPARENCY.
(4) FROM 2-1/4 X 2-1/4 INCH NEGATIVE.
(5) ANAMORPHIC.

Figure 10.1-24 Common projection formats.

SCREEN IMAGE WIDTH (IN.)	LENS FOCAL LENGTH (IN INCHES)							
	1/2	1	1 1/2	1 5/8	2	2 1/2	3	4
	PROJECTION DISTANCES (IN FEET)							
12	1½	2¾	4¼	4½	5½	7	8½	11
16	1¾	3¾	5½	6	7½	9¾	11	15
20	2¼	4½	6¾	7½	9	11	14	18
30	3½	6¾	10	11	14	17	20	27
40	4½	9	13	15	18	22	27	36
50	5½	11	17	18	22	28	33	45
60	6¾	13	20	22	27	33	40	53
72	8	16	24	26	32	40	48	64
96	11	21	32	35	42	53	64	85
120	13	27	40	43	53	66	79	106
144	16	32	48	52	64	79	95	127

A) 16 MM FILM

SCREEN IMAGE WIDTH (IN.)	LENS FOCAL LENGTH (IN MILLIMETERS)						
	15	17½	20	22	25	28	32
	PROJECTION DISTANCES (IN FEET)						
12	3	3½	4	4½	5	5½	6½
16	4	4½	5¼	5¾	6½	7½	8½
20	5	5¾	6½	7¼	8¼	9¼	10½
30	7½	8½	9¾	11	12	14	16
40	9¾	11	13	14	16	18	21
50	12	14	16	18	20	23	26
60	15	17	20	21	24	27	31
72	18	20	23	26	29	33	37
96	23	27	31	34	39	44	50
120	29	34	39	43	49	54	62
144	35	41	47	51	58	65	75

B) SUPER 8 MM FILM

LENS FOCAL LENGTH (IN INCHES)								SCREEN-IMAGE WIDTH (IN INCHES)			
1.4	2	3	4	5	7	9	11	135–35MM	126	SUPER-SLIDE	SINGLE-FRAME FILMSTRIP
PROJECTION DISTANCES (IN FEET)											
2	3	4	5½	7	10	12½	15½	20	15½	22	13½
3	4	6	8	10	14	18	22½	30	23	33½	20
3½	5½	8	10½	13	18½	24	29	40	31	44½	27
4½	6½	10	13	16½	23	29½	36	50	39	55½	33½
5½	8	11½	15½	19½	27	35	42½	60	45	60	40
6½	9	14½	18	23	32½	41½	51	72	56	80	48
8½	12	18½	24½	30½	42½	55	67	96	75	87	64
10½	15	23	30½	38	53	69	84	120	93	132	81
12½	18	27	36½	45½	64	82	100	144	112	160	96

C) SLIDES

Figure 10.1-25 Screen image widths for various lens focal lengths and various film and slide formats.

larger film formats such as the 35mm slide projector. To avoid large lamp diameters, a hybrid condensing scheme is used in which the optical power is divided between the lamp reflector and a lens as sketched in Figure 10.1-27. Design theory of these systems is beyond the scope of this review. Frequently, the lens is referred to as a relay lens although this is a misnomer since the lens does not act as the relay lens of classical optics.

Occasionally, when the volume of lamps required for a projection device does not warrant a new lamp type but existing lamps do not meet the optical requirements, it may be possible to use a corrective lens in conjunction with an existing lamp in a hybrid system. This technique has proved useful in the microfilm field.

Another hybrid condensing system is shown in Figure 10.1-28. A paraboloidal reflector produces nearly-collimated light. Then a positive lens converges the light onto the film gate. Here, as in other systems with deep reflectors, no image of the source is formed. The advantage of this approach is that two or three lamps can satisfy the needs of many optical devices. Design techniques are based on flux-transfer concepts, but empirical tests guided by experience often are adequate to develop a new system.

The various Tru-Beam lamps use one of three surface finishes: smooth, peened, or faceted. Figure 10.1-29 illustrates these three types of finishes. A smooth finish is appropriate for small film formats since each point of the gate and its conjugate screen point receives light from a large fraction of the reflector. This averages out the non-uniform luminance over the helical filament.

In projection systems with larger formats, it is common for a smaller fraction of the reflector surface to contribute light to each film gate point. This can cause significant illuminance non-uniformities over the screen. If the field were smoothed by a diffuse reflecting surface such as an etched reflector, too much light would be scattered out of the optical system. However, peening or faceting maintains the specularity of the surface while providing 'diffusion' within a limited solid angle.

Peens and facets are similar in that they locally modify the optical power of a reflecting surface. The principal optical effect is a function of the ratio of the average element width to the radius of curvature and of the relation of the average element size to the angular size of the source subtended at that element. Peens often have slightly random boundaries and have virtually no limits on local curvature. Facets have precisely defined boundaries and usually have little or no local curvature. Thus, the facet generally has less freedom of design than the peen.

Facets or peens can be arranged in a variety of geometric forms, rectangular, hexagonal, etc. and in straight lines, in staggered patterns, etc. Such arrangements have minor effect on the smoothing power of the surface. In borderline situations, a highly regular facet array may not do as complete a job of smoothing the field pattern as staggered arrangements of facets or the more random arrangement of peens depending on the symmetries that exist between the facet pattern and the source of the nonuniformities.

Slide Projectors

In designing a slide projector, the lamp chosen is of major importance. If a tungsten-halogen lamp is used, the luminance will be high, but the typically small filament size will require a large condenser magnification to fill the lens with the filament image. In under-fill conditions, the advantage of using a large-aperture (fast) lens is lost. However, lamp placement is not critical. In inexpensive designs using Kohler illumination, it is not unusual to use a small filament to under-fill the system, plus a concave mirror behind the lamp to form another image of the filament in the lens. The gain due to such an external reflector often is not great due to poor reflector alignment, losses in passing through the lamp envelope, direct blockage by the filament, reflector surface deterioration, etc.

Filmstrip Projectors

Filmstrips have a series of 18 x 24mm frames which are projected individually. The usual focal length of the projector lens is about 3". A transport mechanism is provided to advance the film as well as a framing device to center the frame being projected. The optics are similar to other slide projectors.

16mm Projectors

Projectors for 16mm film usually employ Tru-Beam type lamps on the order of 250 watts with the projection lens typically about a 30mm,

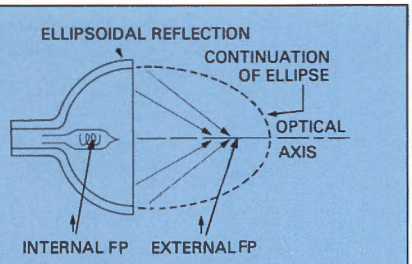


Figure 10.1-26 Cut-away view of Tru-Beam (Rim-mount Type) lamp.

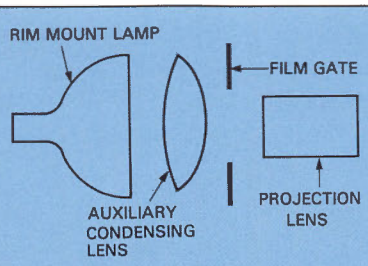


Figure 10.1-27 Hybrid condensing system for large film formats.

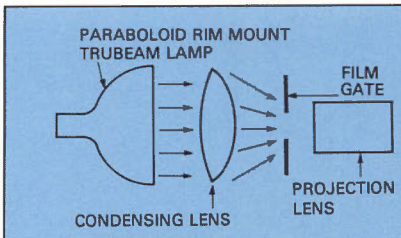
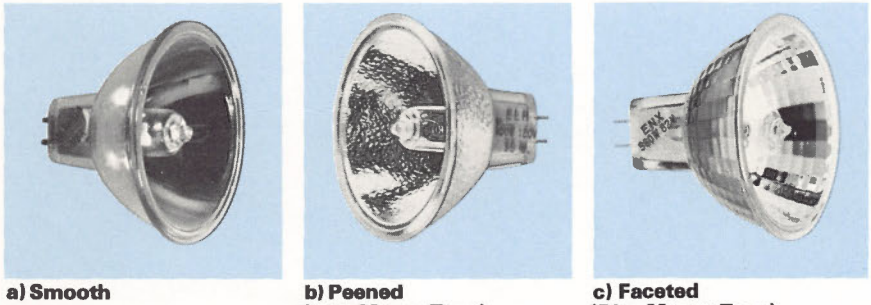


Figure 10.1-28 Paraboloidal Tru-Beam condensing system. The focal length of the condensing lens is approximately equal to the spacing between the condensing lens and the projection lens.



a) Smooth

b) Peened (Rim-Mount Type)

c) Faceted (Rim-Mount Type)

Figure 10.1-29 Tru-Beam reflectors.

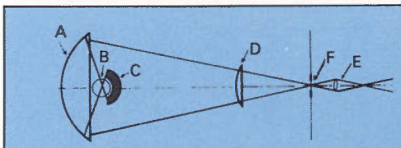


Figure 10.1-30 Arc-type 35mm motion picture projector:
A) ellipsoidal reflector; B) light source; E) projection lens; F) film gate. If the source is a xenon short-arc lamp, the auxiliary reflector (C) and auxiliary condenser (D) may be used.

f/1.2. Claw pull-downs are generally used, with a rotating shutter and one or two flicker blades to cut off the light while the film is being moved to the next frame and to increase the flicker frequency to 48 exposures per second, i.e., above the critical fusion flicker frequency. Silent film operates at 16 frames per second while sound film operates at 24 frames per second.

35mm Motion Picture Projectors

Due to the longer throws and the larger screens generally associated with 35mm projection, sources of greater luminance than incandescent lamps are required. In the past, the carbon arc was the normal source for 35mm motion picture projection. The disadvantages of consumable carbon rods, combustion byproducts, etc. have caused a recent trend to the more convenient short-arc xenon lamp. The typical optical system in such projectors is of the Abbe form illustrated in Figure 10.1-30.

8mm Projectors

Super-8mm and 8mm projectors are usually intended for the amateur film market. Claw pull-downs are used, sometimes without spockets. The standard film speed is 18 frames per second for silent films and 24 for sound. A lamp with a built-in ellipsoidal mirror is commonly used to condense or concentrate the light in the vicinity of the gate. 8mm projection lenses have typical focal lengths of 22mm and speeds of f/1.2.

Sound Track Excitation

Optical sound track excitation is accomplished by the modulation of a small source of light on a detector using a track of photographic density as the attenuator. The frequency of the desired sound has a corresponding density variation associated with it, and the internal electronics convert the light modulation into sound. Magnetic sound uses a magnetic track alongside the film in conjunction with a tape head on the projector.

8mm and Super-8mm use a film speed of 24 frames per second, with the sound track recorded 56 frames ahead of the corresponding frame for regular 8mm and 18 frames ahead for Super-8mm. Because of the narrow space available, magnetic sound reproduction is used.

16mm projectors often use optical sound. Sound films run at 24 frames, with the optical sound track recorded 26 frames ahead and the magnetic sound track recorded 28 frames ahead.

35mm projectors are mostly of the magnetic sound type, since noise reducers, stereo and quad effects, etc. can be easily added on. The sound record is placed on the film 21 frames ahead of the corresponding picture.

Projection Screens

The requirements of the particular projection system generally dictate the type of screen to be used. Screens for rear projection are translucent, and screens for front projections are opaque. The various opaque screens available include matte-white, glass beaded, metallized, semi-glass, and lenticulated types.

The term 'gain' is used to compare a particular screen with a perfectly reflecting or transmitting (lossless), completely diffuse (Lambertian) screen in which the incident illumination produces equal luminance in all directions. Thus, the gain of a screen is a directional property. To completely describe a screen, the gain must be specified throughout the range of viewing angles. However, the single-number nominal gain frequently used to describe screens is that in the direction of maximum luminance. The gain distribution is also a function of the direction from which the screen is illuminated; consequently, this must be specified also.

The perfect diffuser would yield $1/\pi$ cd/ft² (i.e., 1 fL) of reflected light at all angles for each lumen/ft² (i.e., fc) of incident light, or a gain of unity in all directions. Screen luminance diagrams graphically show the departure from this reference condition; these are graphs of luminance with respect to angle.

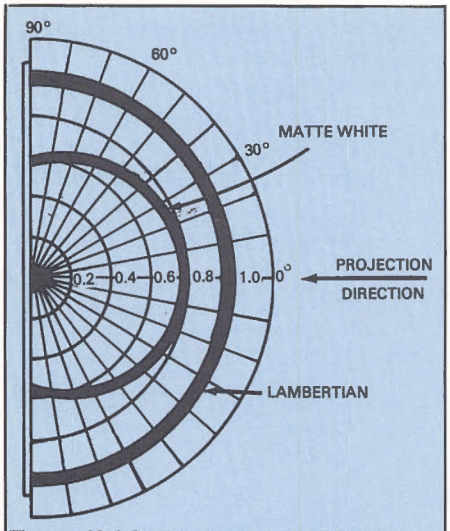


Figure 10.1-31 Luminance distribution of matte-white paint and of a Lambertian perfect diffuser used as a reference for gain value.

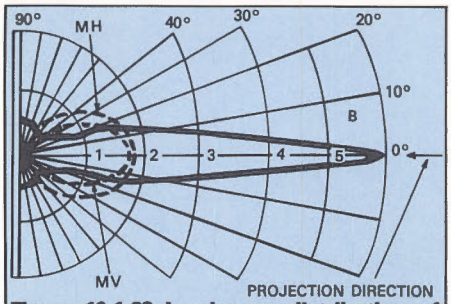


Figure 10.1-32 Luminance distribution of beaded screen (B) and of metallized directional screen in horizontal direction (MH) and vertical direction (MV).

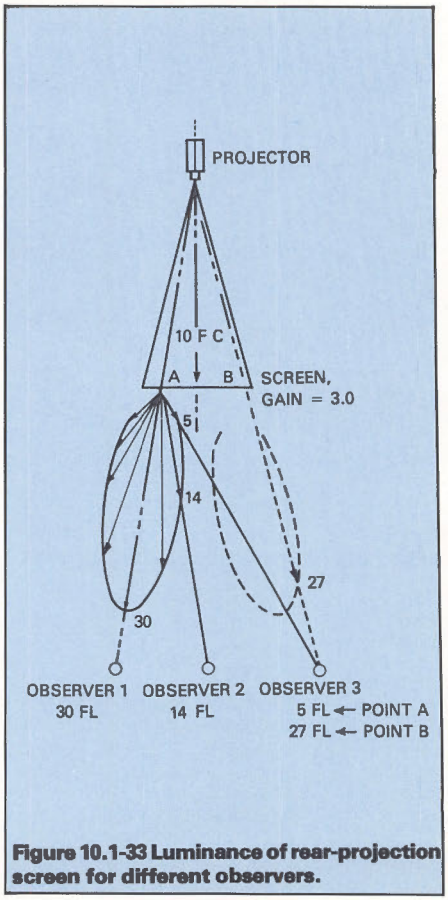


Figure 10.1-33 Luminance of rear-projection screen for different observers.

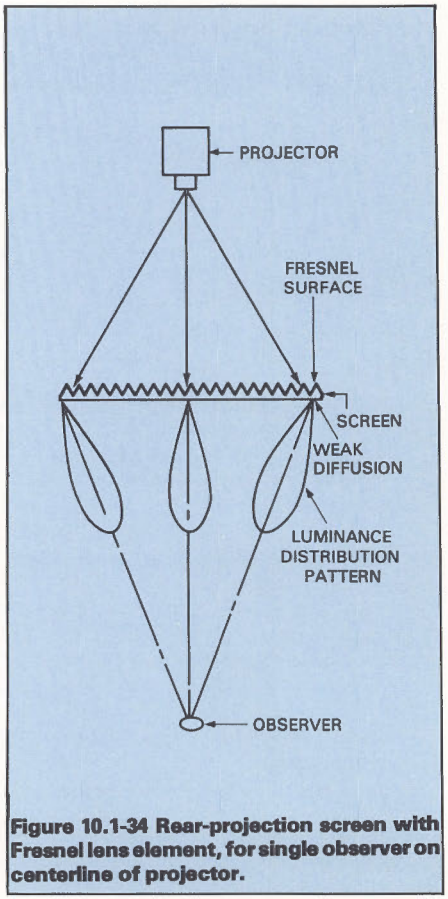


Figure 10.1-34 Rear-projection screen with Fresnel lens element, for single observer on centerline of projector.

Matte-white screens closely approximate the ideal screen, as shown in Figure 10.1-31, typically producing an on-axis gain between 0.75 and 0.90. These screens are recommended where viewers are spread over a wide angle in the viewing area.

Semi-matte screens incorporate a material in the paint to give the screen a slight gloss. In this way, the field pattern is more directional than the matte screen, and gain is increased to about 1.5 to 2.

Metallized screens use a metallic pigment either mixed in with the paint or applied to the screen surface. This screen is directional, as illustrated in Figure 10.1-32. Its properties can be controlled somewhat, though 'hot spots' are generally produced at the specular angle from the projector direction. Lenticulated screens are metallized screens having small shaped geometric patterns embossed evenly on the screen surface. These control the reflection of light to spread over a range of angles as required.

Beaded screens are made with small glass or plastic spheres which are essentially retroreflectors with some spread, and they reflect light in the general direction of the projector. These screens will be very bright when viewed along the projection axis; gains of 5 to 15 are typical. However, the penalty for high gain is limited viewing direction, and the luminance falls off very rapidly as shown in Figure 10.1-32. These screens are suitable in homes or some classrooms where small viewing angles are common and ambient light levels can be high.

Rear-projection screens may be lenticular or diffusing (glass or plastic substrates to which a diffusing layer is applied), with gains in the order of 3 to 25. These screens are also highly directional. Figure 10.1-33 illustrates some of the properties for a screen with a gain of 3.0. Note that observers 1, 2, and 3 each see point A at a different luminance. However, even a single observer will not see a uniform screen. Observer 3 sees point A at 5fL but sees point B at 27fL.

The uniformity of rear-projection screens can be greatly increased by increasing the diffusion. This reduces the gain and spreads the light. However, the losses are much greater than when this is done for front-projection screens since increasing the diffusion decreases screen transmittance, i.e., more light is reflected back toward the projector.

A high-gain screen which is nearly uniform across the screen can be made providing the observer position is known. This is often the case with devices such as microfilm readers where a single observer is in a reasonably fixed location. A Fresnel-type lens is incorporated in the screen to direct light from the projector toward the fixed viewing location. This is illustrated in Figure 10.1-34.

Screen Luminance

Measurements of screen luminance normally are made from the centerline of an auditorium or viewing area to the center of the screen for many standard evalulations. ANSI-recommended levels of screen luminance are available for various situations, e.g., 16 ± 2 fL for indoor theatres and 5fL for slide and slide film projection.

It is possible to estimate the required screen lumens by assuming a uniform screen, using screen gain to calculate screen illumination, and then multiplying illumination times screen area for screen lumens. An exact calculation is complex since it must be taken into account variations in screen illumination, the exact gain for viewing and projector directions, etc.

Darkroom Applications

Generally, darkroom walls and ceilings are painted white so as to reflect as much of the safelight illumination as possible. Light-tight darkrooms are a must.

Safelights should transmit light which will have the least effect on photographic materials to prevent fogging of the film. This is accomplished by selecting a safelight filter or lamp which produces light at visible wavelengths where the spectral response of the film is a minimum. Safelights should produce just enough light to be able to maneuver in the dark.

Safelights use either low-wattage incandescent bulbs with colored envelopes or clear bulbs behind colored filters. In addition, they may provide either general or local illumination in parts of the darkroom depending on the nature of the work.

Film manufacturers often state the safelight requirements for the particular photosensitive material to be used. This will often consist of a lamp-filter combination, or in the case of colored bulbs, the color and wattage.

Enlarging

Enlargers are essentially projection systems, and the previous discussion of projection systems generally applies. The approximate exposure time can be determined (from ANSI PH 2.2-1972) by

$$t = \frac{92}{E_{av} S} \qquad \text{(eq. 10.1-12)}$$

where **t** is the time in seconds, E_{av} is the average illumination at the image in lm/ft² (fc), and **S** is the ASA paper speed. Equation 10.1-10 can also be used to determine illumination for a given design. Exposure time is frequently in the 10-20 second range for average-contrast negatives.

Condenser enlargers use incandescent lamps with ratings from 75 to 1000 watts. Enlargers can also be of the diffuse condenserless type. A diffusing plate such as opal glass is placed directly above the film gate with a lamp located behind ths diffuser. Due to this diffusion, an appreciable fraction of the light is scattered and not collected by the projection lens thus reducing efficiency.

Enlargers, even of the condenser type, often are designed to use incandescent lamps with diffuser lamps. This is to improve uniformity over the field, a prime requirement of enlargers. Enlargers with diffusion of the light incident on the transparency, as opposed to the quasi-directional pure Kohler form, slightly reduce print contrast; this is sometimes known as the Callier effect.

10.2 Reprographic Applications

Reprography is the technology of copying from original materials such as typewritten sheets, printed pages, etc. Reprographic methods are employed not only in office copying machines, but in the printing trades, in the computer industry, and in facsimile transmission systems (e.g., telephone line document copiers.) This section briefly describes some commonly used reprographic processes, and notes the applicable characteristics of lamps used as light sources in those processes.

Reprographic machines generally have internal light sources, frequently tubular fluorescent lamps (often of the aperture type) or tubular tungsten-halogen lamps (sometimes with segmented filaments), that provide the radiant energy required for copying. This radiant energy can be used to make copies by direct transmission through originals, or by reflection from originals ('reflex copying'), depending on the process employed. The levels and spectral distributions of radiant energy required to make copies are dependent on the absolute spectral sensitivities of each process. Tungsten-halogen lamps are generally suitable for reprographic processes requiring radiant energy of longer wavelengths such as the red and infrared, while fluorescent lamps are generally suitable for processes requiring radiant energy of shorter wavelengths such as the blue, violet, and ultraviolet.

Basic Copier Processes

The major copier processes employ one or more of the following mechanisms: electrostatic, thermal, and photochemical (including photochromic and photopolymerization process). Some of the most common processes are described below and illustrated in Figure 10.2-1.

Indirect or transfer electrostatic processes: reflected light from the original dissipates charge in the non-image areas of an electrostatically-charged photoconductive intermediate surface made of a photosensitive organic material or of selenium (in which case, the process is called 'xerography'). The remaining charge on the intermediate surface forms a latent image. Thermographic powder is applied to the surface of the intermediate where it adheres only to the charged latent-image areas. The powder image is then transferred to plain paper which is heated to convert the powder into a permanent thermographic image. Indirect or transfer electrostatic processes require radiant energy levels of about 1.0×10^{-7} W-sec/cm² at the surface of the photosensitive material to produce the latent image.

Xerography is an indirect electrostatic process using a drum coated with photoconductive selenium which is used as a transfer medium for the image. The drum is first electrostatically charged to a high positive voltage, and then it is illuminated by light reflected from an original through a lens-and-mirror optical system. The light reflected from the bright non-image areas of the original causes the positive charges to dissipate, leaving charges in a pattern corresponding to that of the image on the original. Next, negatively-charged, finely-dispersed dry toner particles are attracted to the positively-charged image areas on the drum. The dry toner

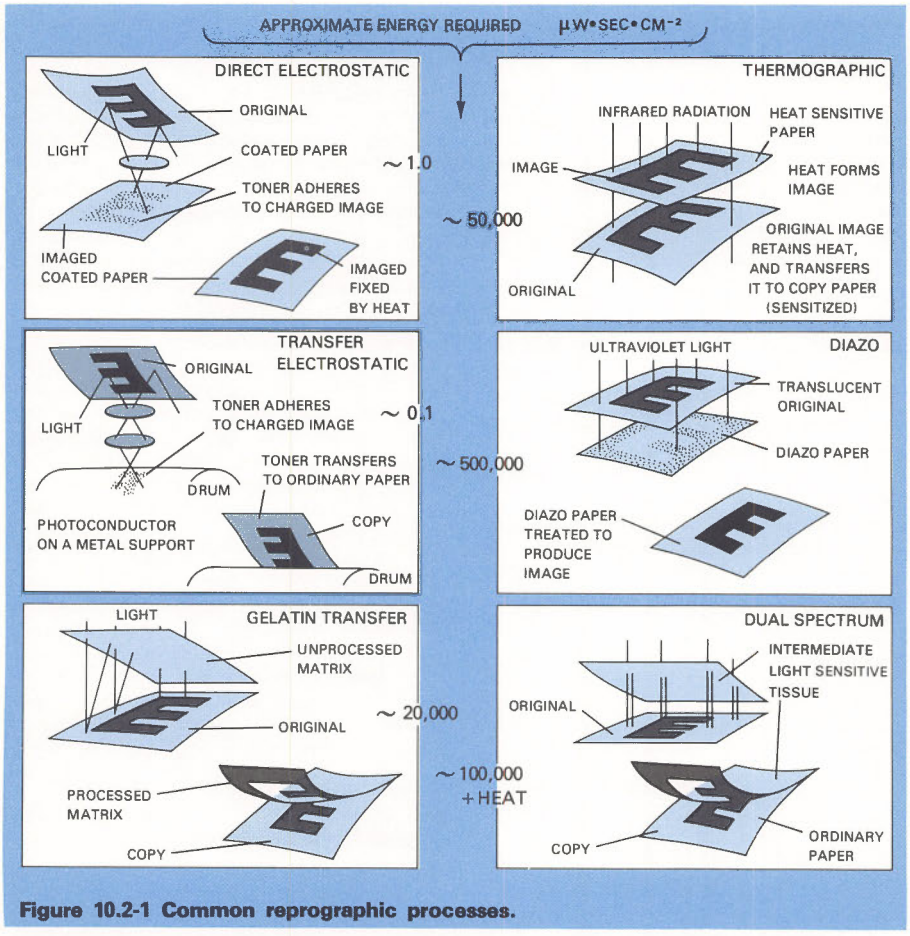


Figure 10.2-1 Common reprographic processes.

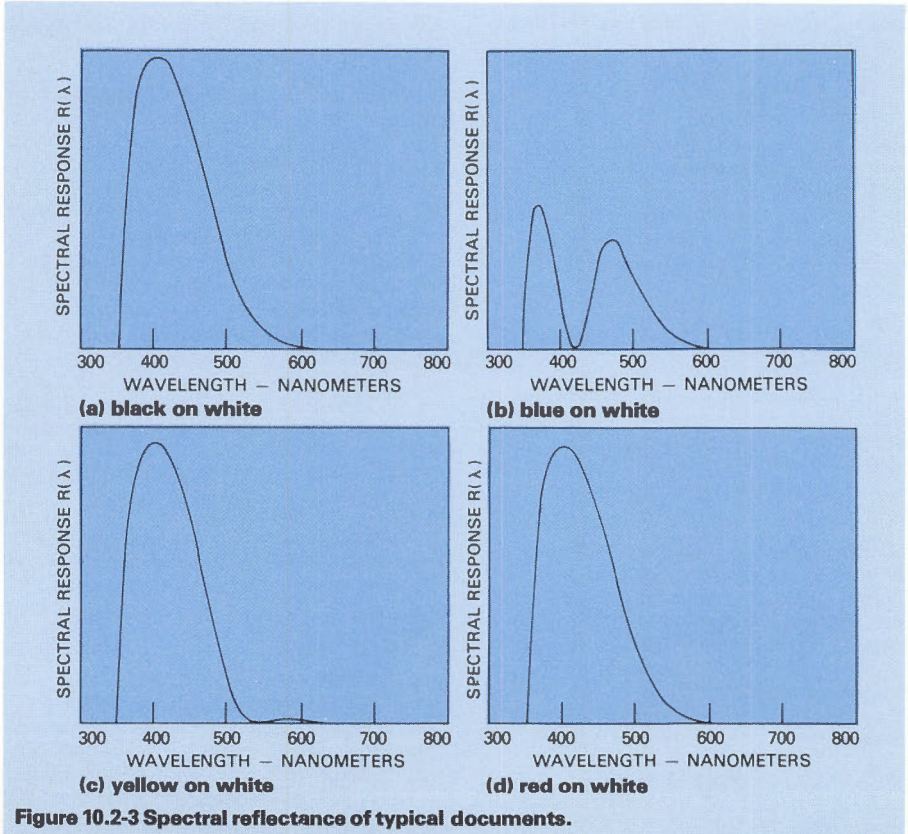

SPECTRAL RESPONSE R(λ)
300 400 500 600 700 800
WAVELENGTH — NANOMETERS
(a) black on white
(b) blue on white
(c) yellow on white
(d) red on white

Figure 10.2-3 Spectral reflectance of typical documents.

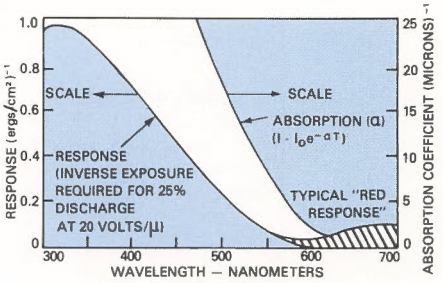


Figure 10.2-2 Spectral response of xerographic selenium drum.

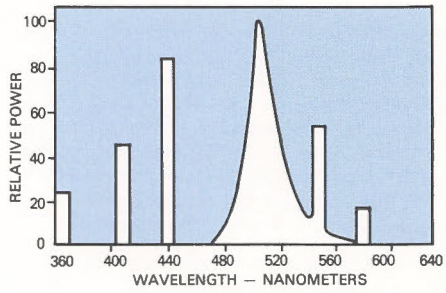


Figure 10.2-4 SPD of F40 fluorescent lamp with 213 phosphor for use as light source in xerographic processes.

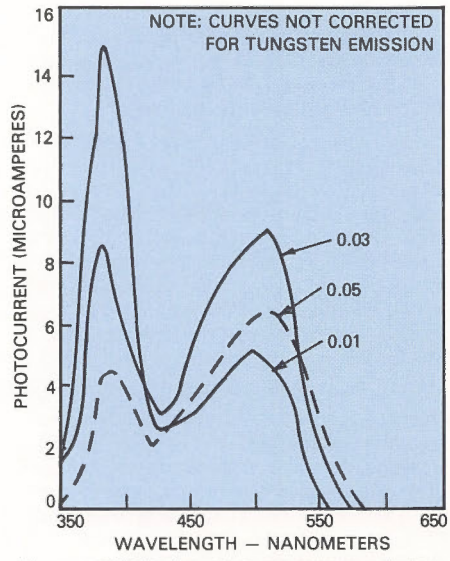


Figure 10.2-5 Spectral response of dye-sensitized electrofax layers with dye concentrations of 0.01, 0.03, and 0.05 grams of fluorescin per 120 grams of Zn0.

Acknowledgements

Figure 10.2-1
From **Modern Office Procedures,** Sept. 1973

Figures 10.2-2 & 10.2-5
Authors: John H. Dessaver & Harold E. Clark
Title: Xerography and Related Processes
Permission of Focal Press, London

Figure 10.2-6
Author: Jaromar Kosar
Title: Light-Sensitive Systems
Publisher: John Wiley and Sons

is then transferred to a charged copy paper which is brought into contact with the drum. The transferred toner is finally fused by heat to the copy paper while the drum rotates past a light source which discharges it so that it is ready for another cycle. Aperture lamps with special phosphors and other special features have been most successful in this application.

Figure 10.2-2 shows the spectral response of the selenium drum. The spectral reflectance of white paper originals with images of various colors shifts the overall spectral response of the system to longer wavelengths as shown in Figure 10.2-3. The spectral power distribution of the fluorescent lamp phosphor required to match the overall spectral response of xerographic systems is shown in Figure 10.2-4.

Gelatin transfer process: light reflected from the original affects a chemically-treated intermediate which is then used to transfer an image to copy paper. Gelatin transfer processes require about 2.0 x 10^{-2} W-sec/cm² to produce the latent image on the intermediate.

Thermographic process: Heat-sensitive paper is placed in close contact with the original, and the original is irradiated with infrared radiation through the heat-sensitive paper. The infrared radiation passes through the heat-sensitive paper and is absorbed by the image areas of the original causing the image areas to be heated. The hot image areas then heat those portions of the thermographic paper that are in contact with them causing the formation of corresponding images in the thermographic paper. Thermographic processes require about 5 x 10^{-2} W-sec/cm² to produce the image on the thermograpic paper.

Photographic (silver-halide) process: light is reflected from the original to the surface of film or paper coated with silver-halide crystals. The light frees electrons from bound states in the silver-halide lattice, but those free electrons remain trapped within the crystals neutralizing silver ions and forming latent images of metallic silver. These latent images act as development centers which permit a chemical developer to convert entire silver halide crystals into images of metallic silver. The silver-halide crystals that were not affected by the light are removed by a process called 'fixing'. Photographic copying processes require about 1.0 x 10^{-8} W-sec/cm² to form the latent image.

Direct electrostatic processes. Light is reflected from the original to photoconductively-coated paper which is electrostatically charged. The light reflected from the non-image areas in the original dissipates the charge in the corresponding areas of the photoconductively-coated paper; the remaining charge forms a latent image on the coated paper. Finely dispersed thermographic ink powder is then applied to the surface of the coated paper where it adheres only to the charged latent-image areas. The ink powder is heated and melts, being converted into a permanent thermographic image on the paper. Direct electrostatic processes (e.g., Electrofax) require radiant energy densities of about 1.0 x 10^{-6} W-sec/cm² to produce the latent image on the coated paper.

Electrofax, the oldest and most widely used direct electrostatic process, employs a zinc-oxide-coated paper instead of the selenium drum used in xerography. There is no image transfer because the coated paper itself is first charged and then discharged by light reflected from the original. This process is widely used although the treated paper is more expensive than the plain paper permitted by xerography. The spectral response of typical electrofax systems is shown in Figure 10.2-5. As in Figure 10.2-3, most originals shift the overall spectral response to longer wavelengths. Therefore most zinc-oxide-coated paper machines use tungsten, tungsten-halogen, or xenon flash lamps, the spectral outputs and intensities of which match the requirements of the zinc-oxide-coated paper process.

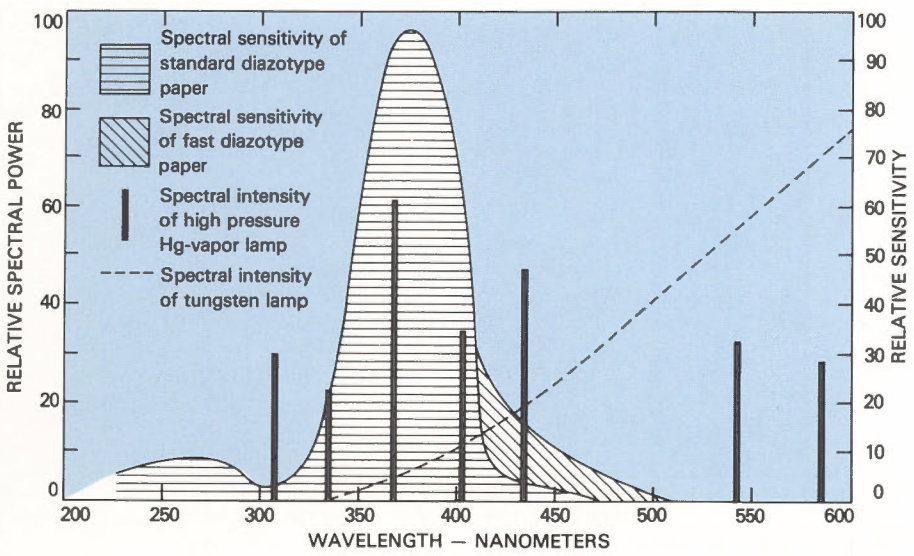


Figure 10.2-6 Spectral sensitivity of typical diazo papers.

Diazo processes: a transparent or translucent original with opaque image areas is placed in contact with the sensitized surface of paper coated with a diazonium salt. The sensitive paper is irradiated with ultraviolet radiation through the original except where the radiation is blocked by the opaque image areas of the original. The coated paper is then heated or chemically processed to convert the unexposed salts to visible images and bleach out the exposed areas. Diazo processes require about 0.5 W-sec/cm² to form the latent image. Figure 10.2-6 shows the spectral sensitivities of typical diazo papers.

Diazo whiteprint processes produce blue or sepia images on white background. They have almost completely replaced the older blueprint and brownprint processes, both of which required complicated post-exposure treatment.

Kalvar ® process: a diazonium salt uniformly dispersed in a thermoplastic layer is decomposed by exposure to ultraviolet radiation producing a latent image of nitrogen gas bubbles which are trapped within the plastic layer. The latent image is 'developed' into a visible image by application of heat which softens the thermoplastic layer permitting the nitrogen to expand into light-scattering bubbles. The Kalvar process requires about 0.1 W-sec/cm² to form the latent image.

Photo intermediate processes: light affects a coated intermediate which is then contacted to specially-coated copy paper, and the image is transferred by heat (dual-spectrum process), direct diffusion (diffusion-transfer process), or by chemical means. Photo intermediate processes require about 0.1 W-sec/cm² to produce the latent image.

Dye imaging and dye transfer processes: light affects dyes which are fixed or transferred to produce copies. These processes require about 1 x 10^{-4} to 6 x 10^{-2} W-sec/cm².

Persistent internal polarization process employs phosphors such as zinc cadmium sulfide to coat paper or non-expendable drums which are exposed to light; an applied electric field forms polarized image patterns which attract charged toner particles. This process requires about 2 x 10^{-6} W-sec/cm².

Photopolymerization processes are used to produce plates, intermediates, or images by means of chemical or thermal transfer steps or by light or chemical deactivation steps. These processes require about 1 x 10^{-3} to 6 x 10^{-2} W-sec/cm².

Electroprinting and electrophotography employ forms of dye-sensitized zinc oxide which is used as a sprinkled powder after point charging to attract inks or pigments. The zinc oxide particles are sometimes interspersed in a dielectric layer. These processes require about 2 x 10^{-6} W-sec/cm².

DuPont Dylux ® process uses radiation to form permanent colored images. Ultraviolet radiation is used to initiate a free radical reaction which culminates in the formation of dye molecules. The image generated is immediately usable. Visible radiation stabilizes the image. The process requires about 3 x 10^{-2} W-sec/cm².

Design Considerations of Fluorescent Lamps for Reprographic Applications

The design of a reprographic system such as a copier involves compromises among the following major factors:

(1) lamp exitance (radiant power output per unit area), (2) lamp efficiency (radiant power out/electrical power in), (3) system economics (e.g., lamp cost and useful life, cost of starting circuits and other auxiliary circuits), (4) external dimensions of copier, (5) optical system (optical path lengths and 'speed' of the optics), (6) total energy requirements of copier (for lamps, motors, heaters, etc.), and (7) spectral compatibility of lamp radiant output and radiation sensitive reprographic materials.

Radiant Exitance

The irradiance (radiant flux incident per unit area) which causes formation of images on the optical-radiation-sensitive materials used in reprographic processes is determined by the radiant exitance (radiant flux or radiant power output per unit area) of the lamps employed, by the number and spacing of those lamps, by the various optical path lengths involved, and by the 'speed' of the optical system. The radiant exitance that a fluorescent lamp can produce is determined by (1) lamp dimensions and design, (2) the phosphor, (3) reflector coatings and apertures that modify polar distribution, (4) electrical operating conditions (especially input loading), (5) thermal operating conditions, and (6) age in terms of number of starts and total burning time. These factors are discussed in the following paragraphs.

Lamp dimensions and design are restricted to certain practical types of configurations by the physics of low-pressure mercury discharge phenomena. Aside from the basic need to produce only enough electrons to maintain conduction in the fill gas, the primary objective is to produce the largest possible number of ultraviolet photons (mainly at 253.7 nm) that excite the phosphor. This is accomplished by controlling the field strength and current density which are generally not affected by the overall shape of the lamp (e.g., straight, circular, or U-shaped) but by the bulb diameter and length, the electrode (coil) design, the fill gas composition and pressure, and the input loading in watts per unit length. Sylvania processing capabilities for straight tubular fluorescent lamps of various bulb diameters and lengths are shown in Figure 10.2-8 along with typical loadings. Although loadings up to 20% higher than the tabulated values have been used successfully, there is usually a sacrifice in system costs, useful lamp life (e.g., light output maintenance and end discoloration), and/or system efficiency. There are no general rules for all types of fluorescent lamps, but effects of the following orders might be expected if lamp loadings exceed those listed in Figure 10.2-8 by more than 20%: physical lamp life will be reduced 35%, useful lamp life will be reduced 25%, and system efficiency will be reduced 15%.

Phosphors vary in conversion efficiency, quantum efficiency, and output maintenance characteristics. The conversion efficiency is largely dependent on the re-radiation wavelength, e.g., the longer the re-radiation wavelength is than the excitation wavelength of 253.7 nm, the lower is the emitted photon energy. The quantum efficiency is based on too many factors to permit generalization and can vary tremendously. However, the better ultraviolet phosphors will produce up to 20% higher radiant exitance than phosphors emitting in the mid-visible region.

Each phosphor has its own output maintenance characteristic which varies with the ultraviolet irradiance, i.e., with lamp current loading as shown for Cool White phosphor in Figure 10.2-9. Note that this data is shown from zero hours for reprographic applications. The values shown are approximate, and the actual values for individual lamps or even for lot averages may vary considerably from the curves.

Electrical operating conditions include power line voltage, lamp starting voltage, lamp operating voltage, and lamp operating current. These determine, and in turn are affected by, the ballast and the starting circuit. Lamp starting is influenced by: (1) electron emission from coil (coil design, coil voltage, starting circuit), (2) ambient conditions (temperature, humidity, lamp surface conditions), (3) type of circuit and fixture (open-circuit voltage, starting-aid design

BULB SIZE	BULB DIAMETER	RANGE OF LENGTHS	INPUT W/CM	INPUT W/FT
T5	5/8″	3.3-36″	0.40	12
T6	3/4″	6-72″	0.46	14
T8	1″	12-96″	0.60	18
T12	1-1/2″	12-96″	0.95	29
T17	2-1/8″	36-60″	1.25	38

Figure 10.2-8 Bulb sizes and lengths of straight tubular fluorescent lamps within Sylvania processing capabilities, and typical loadings for two-foot lamps. The loadings for longer lamps are slightly lower than the tabulated values.

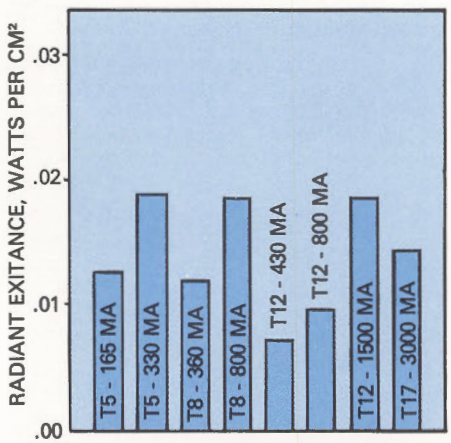


Figure 10.2-7 Radiant exitance of typical fully-coated fluorescent lamps.

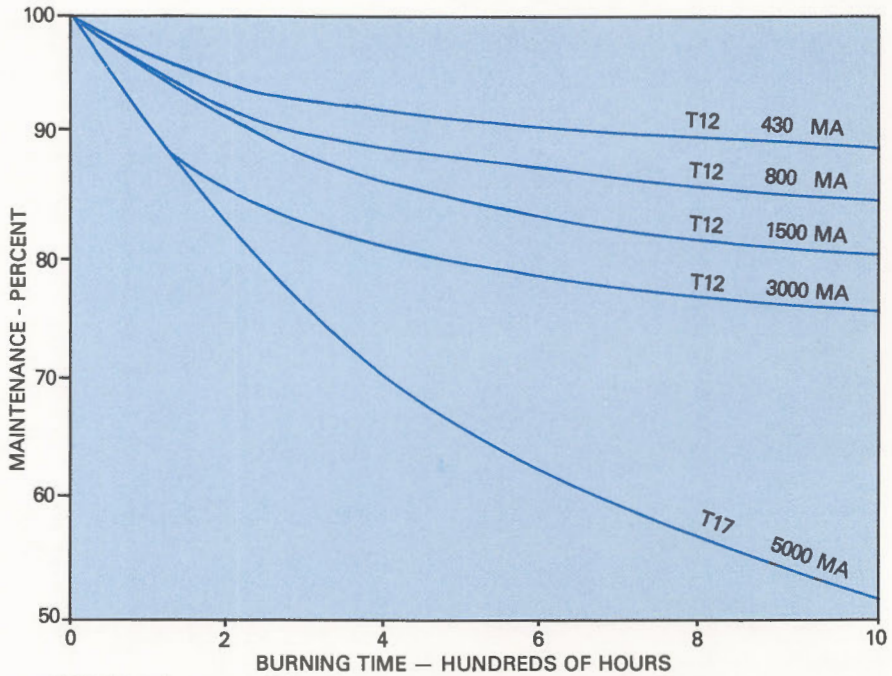


Figure 10.2-9 Maintenance of Cool White phosphor at various loadings.

and voltage, preheat energy), (4) lamp geometry (length, diameter, surface shape), (5) lamp design (coil, mount, fill gas composition and pressure, type of circuit), and (6) lamp and circuit wattage (heat dissipated).

There are at least four basic types of starting circuits used for fluorescent lamps in copier applications; these are the preheat, flashing (modified rapid start), rapid start, and instant start circuits. As shown in Figure 10.2-10, each of these circuits has different delay times for ignition, for rise to noticeable light output, and for time to peak (after noticeable light output). Preheat starting is usually employed in low-speed copiers, and flashing and instant-start circuits are usually used in high-speed copiers.

Thermal operating conditions. Lamp operating temperature inside the copier is determined by the ambient temperature outside the copier, the selfheating of the lamp, and heating of the copier interior by motors, heaters, etc.

Lamp Life

Because lamp life is affected by a large number of factors, the life of a lamp in reprographic service can only be properly evaluated in the copier. The various factors influencing lamp life include: (1) filament design (cathode coating weight capacity, mechanical retention of coating, thermal characteristics, electrical characteristics), (2) lamp dimensions, (3) gas fill composition and pressure, (4) lamp ballast starting voltages (cathode heating, open-circuit voltage, starting aid voltage, type of starting circuit), (5) operating frequency, (6) operating cycle time, (7) wave shapes (crest factors) of operating voltages and currents, (8) starting and operating conditions (temperature and humidity), (9) type of circuit, (10) operating current level, (11) lamp handling, and (12) production variables (lamp to lamp, lot to lot).

Starting circuits have significant effects on lamp life, especially in copier applications which have frequent, short, on-off cycles. Based on limited tests employing cycles of 5 seconds on and 5 seconds off, the approximate life in number of starts for lamps employing different starting circuits is as follows: preheat, 10,000 starts; rapid start, 100,000 starts; instant start, 200,000 starts; flashing start, 2,000,000 starts. The actual values depend on lamp type and circuits, but only the flashing-start circuit is capable of providing millions of frequent, short, on-off cycles and a physical lamp life of approximately 1,000 hours (total on time).

10.3 Micrographic Applications

Micrographics is the technology by which information can be reduced in size, recorded, stored, and later retrieved for display. Microform is a generic term for any material such as film or paper upon which microimages can be recorded. In addition to manual projection of a single data frame, sophisticated systems permit retrieval of a specific microform, search for the specific frame, and display of that frame at the push of a button. Computer-output microfilming (COM) is a recent advance in micrographic technology by which data are assembled by computer and printed directly on microfilm.

Fine-grain high-resolution film, or microfilm, is the principal medium of micrographic systems, but paper is sometimes employed. Original documentation areas easily can be compressed a thousandfold or more on microfilm. With proper processing, microfilms are suitable for archival recording of documents and also can be used as publishing masters to generate duplicate prints.

The intended use of microform dictates many features of the micrographic system: reduction ratio, blow-back ratio, quality level, recording, processing, and retrieval. Figure 10.3-1 indicates the production flow in a typical documentation system. The current range of microforms include roll film, cartridge, cassette, aperture card, microfiche, and micro-opaque types.

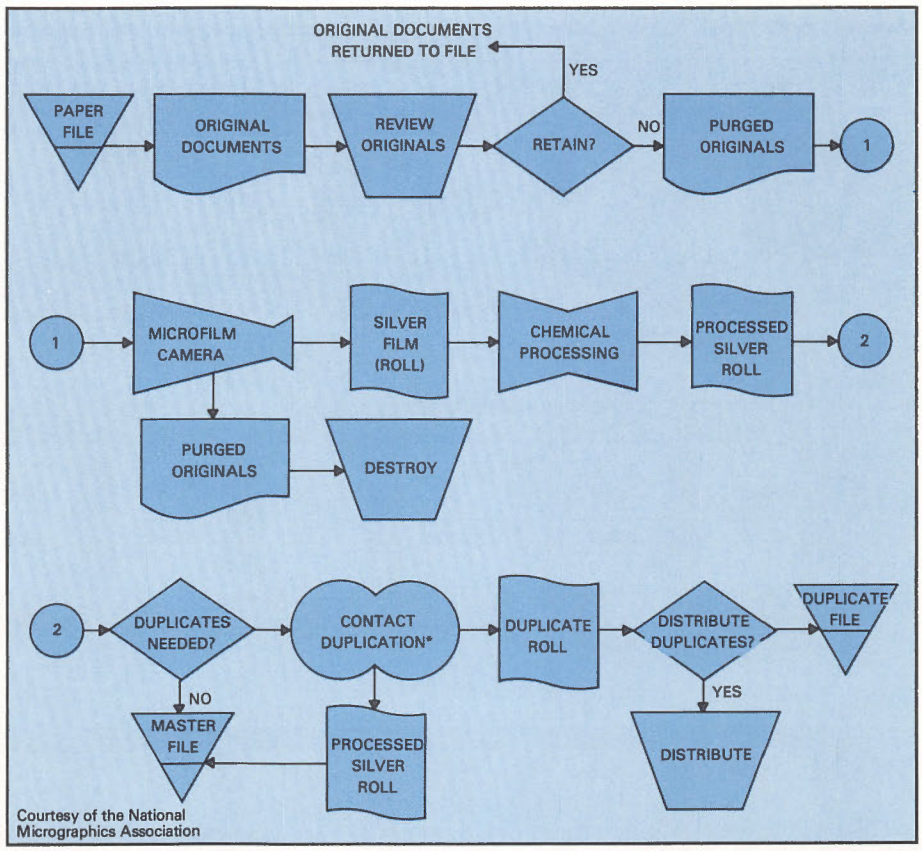


Figure 10.3-1 Flow chart of a basic micrographic system which retains microimages of documents slated for purging or destruction.

TYPE OF LAMP	F8T5	F15T8	F20T12	F18T8/HO	F40T12	F48T12
TYPE OF STARTING	PREHEAT	PREHEAT	PREHEAT	FLASHING	RAPID	INSTANT
TIME TO IGNITE (1)	2±.5 sec.	2±.5 sec.	3±.5 sec.	0	1±.5 sec.	8±4 ms
RISE TIME (2)	0	0	0	8±2 ms	22±5 ms	20±4 ms
INITIAL LIGHT OUTPUT (2)	54±4%	71±6%	84±4%	72±5%	87±3%	84±4%
LIGHT OUTPUT @ 1 MINUTE (3)	88%	93.5%	94%	100%	96%	95%
TIME TO PEAK (4) (5)	2-3/4 ± 3/4 min.	2-1/2 ± 1 min.	6-1/2 ± 2 min.	3/4 ± 0.1 min.	4-1/2 ± 1 min.	6-1/2 ± 1 min.

(1) For appreciable conduction.
(2) Noticeable light output.
(3) Approximate.
(4) After noticeable light output.
(5) L.O. will then drop about 10% for 2 to 3 seconds before it rises to stabilize output.

Figure 10.2-10 Starting characteristics of various fluorescent lamps at 77° F.

Microform size relations can be expressed as follows:

$$\left(\text{Reduction Ratio}\right) = \frac{\left(\text{Projected Dimension}\right)}{\left(\text{Magnification Ratio}\right)\left(\text{Original Dimension}\right)}$$

Reduction ratios can be classified in the following groups:

Low Reduction	Up to 15X
Medium Reduction	15X to 30X
High Reduction	30X to 60X
Very High Reduction	60X to 90X
Ultra High Reduction	90X and up

Roll microfilm is used on reels in standard sizes of 8, 16, 35, 70, and 105 millimeters; 16mm and 35mm are most popular. Reel length of 100 feet is standard, but 200-foot reels are used. Information is usually recorded on microfilm in one of three formats: simplex, duo, or duplex.

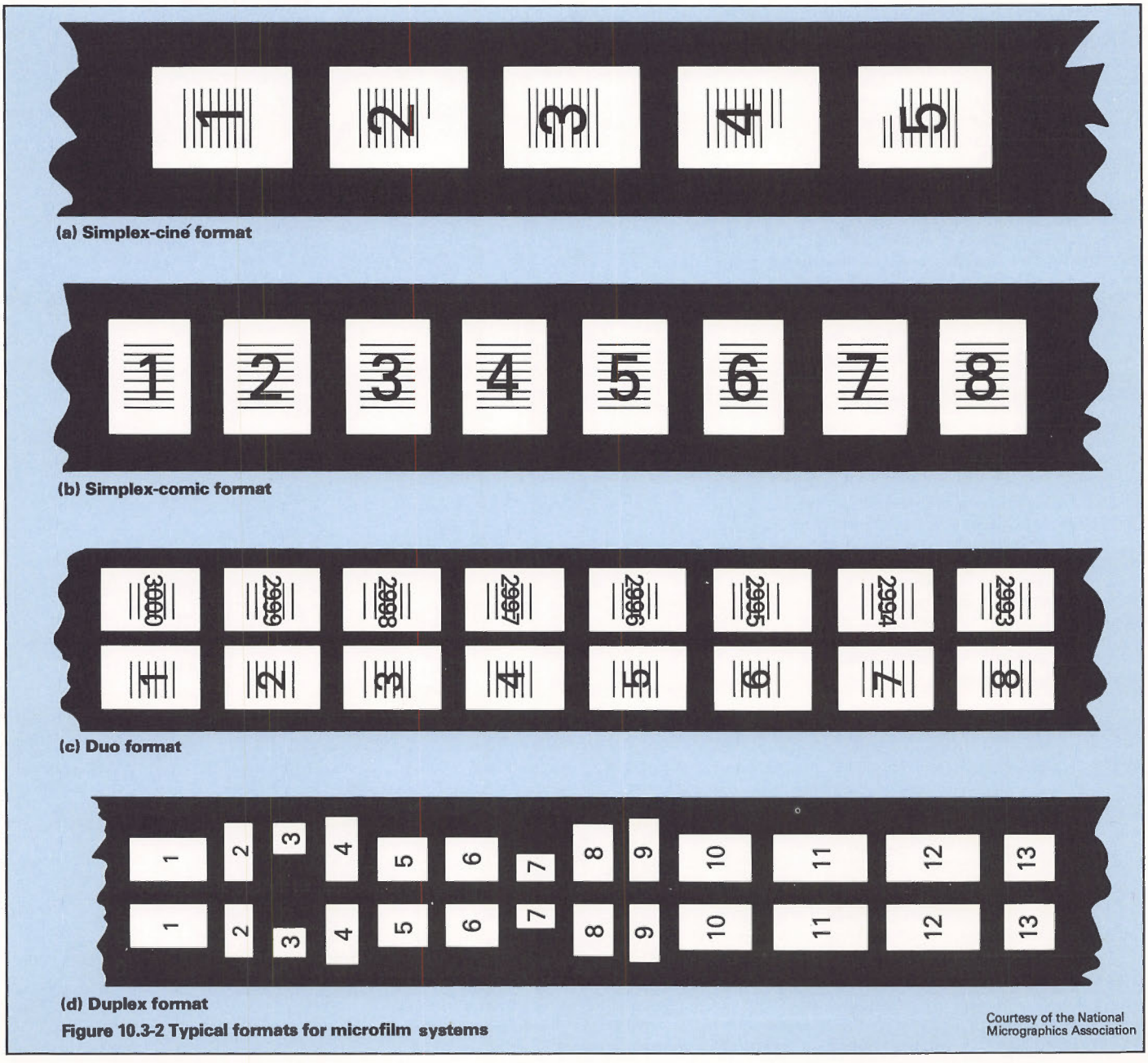
The simplex format has microimages appearing across the width of the film in sequential order. There are two subdivisions: Ciné, or 1A orientation, with motion-picture oriented images and Comic, or 1B, with comic-strip oriented images. In the duo format, film is run through the camera twice with one-half of the film exposed on each passage. Duplex format is used to simultaneously record both the front and the back of the document side by side across the width of the film. Figure 10.3-2 illustrates the various formats.

In the simplex method, one or more pages of a document may be recorded per frame. If two, four, or eight images are recorded for each exposure, these are called 'two-up', 'four-up', or 'eight-up' respectively (see Figure 10.3-3).

Cartridges and cassettes are popular versions of roll film systems, especially in the 16mm size. Cartridges may be inserted directly into the viewer without having to thread the film, and the film must be rewound into the cartridge before it can be removed. Cassettes employ two spools in a plastic housing which is inserted directly into the viewer. Though the user never has to touch the film directly with either system, the cassette affords the added convenience of not requiring the film to be rewound.

Microfiche, i.e., 'small card', is a type of microform which appears in card form. This transparent sheet of film contains microimages in a grid arrangement as shown in Figure 10.3-4. Fiche, as it is frequently called, comes in a variety of sizes; 3 x 5 inches, most commonly 4 x 6 inches, and 5 x 8 inches.

The maximum number of documents which can be recorded is a function of the reduction ratio used. Microfiche recorded at 18X to 48X reductions are most common. Fiche with 90X to 150X reductions are usually called ultrafiche. There are a variety of formats, or image arrangements, used on microfiche: Figure 10.3-5 lists a few of the most common.



(a) Simplex-ciné format

(b) Simplex-comic format

(c) Duo format

(d) Duplex format

Figure 10.3-2 Typical formats for microfilm systems

Courtesy of the National Micrographics Association

Microfiche masters may be prepared by stripping-up roll film or by using a step-and-repeat camera to expose each individual image. It can also be prepared with a special COM recorder on 105mm film which is then cut.

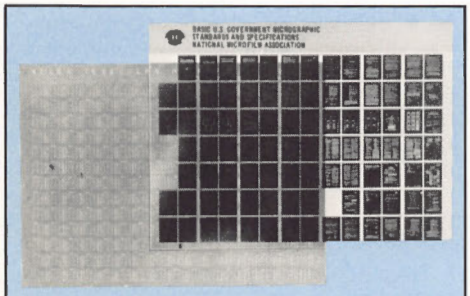
In addition to sheet film, jackets and aperture cards represent other forms of microfiche. An aperture card is an Electric Accounting Machine (EAM) card with microfilm attached over rectangular holes cut in the card. Normal keypunch techniques make for easy sorting and access. A jacket is a transparent plastic carrier with sleeves or pockets to hold microfilm in flat strips. These are convenient forms for storing large documents such as engineering drawings, for assemblying a variety of related data, etc.

Micro-opaques are generated from any standard microfiche and are printed on opaque paper stock. Viewing is by reflected light in special viewers. Micro-opaques are difficult to duplicate, but they have an advantage in that information can be printed on both sides of the card.

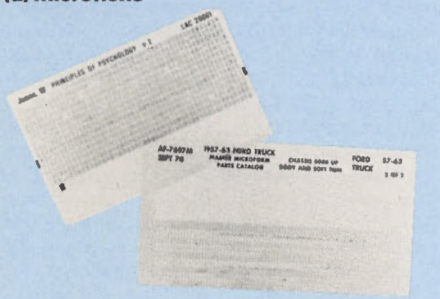
Film stock for microfilm is divided into materials for camera and materials for print use. Camera films usually are of the silver-halide emulsion types because photographic speed is greater than for most alternatives and because such films have good resolution qualities. Print films may be of the silver-halide type or of materials as summarized below.

Silver-halide camera films usually have thin emulsion coatings and fine-grained structure to minimize light scatter. Contrast is high although, in general, film characteristics are a compromise between speed, contrast, spectral sensitivity, and resolution. Print films are similar to camera films, but the contrast is usually lower. Films which retain the same polarity as the original are called direct duplicating films.

Diazo films use a diazonium salt compound coating which is sensitive to ultraviolet energy as illustrated in Figure 10.3-6. These films are designed to be processed in various ways such as development by ammonia, ammonia vapor, heat, or light. High exposure levels are usually required, but the simplified processing procedure makes in-line processing very practical.



(a) microfiche



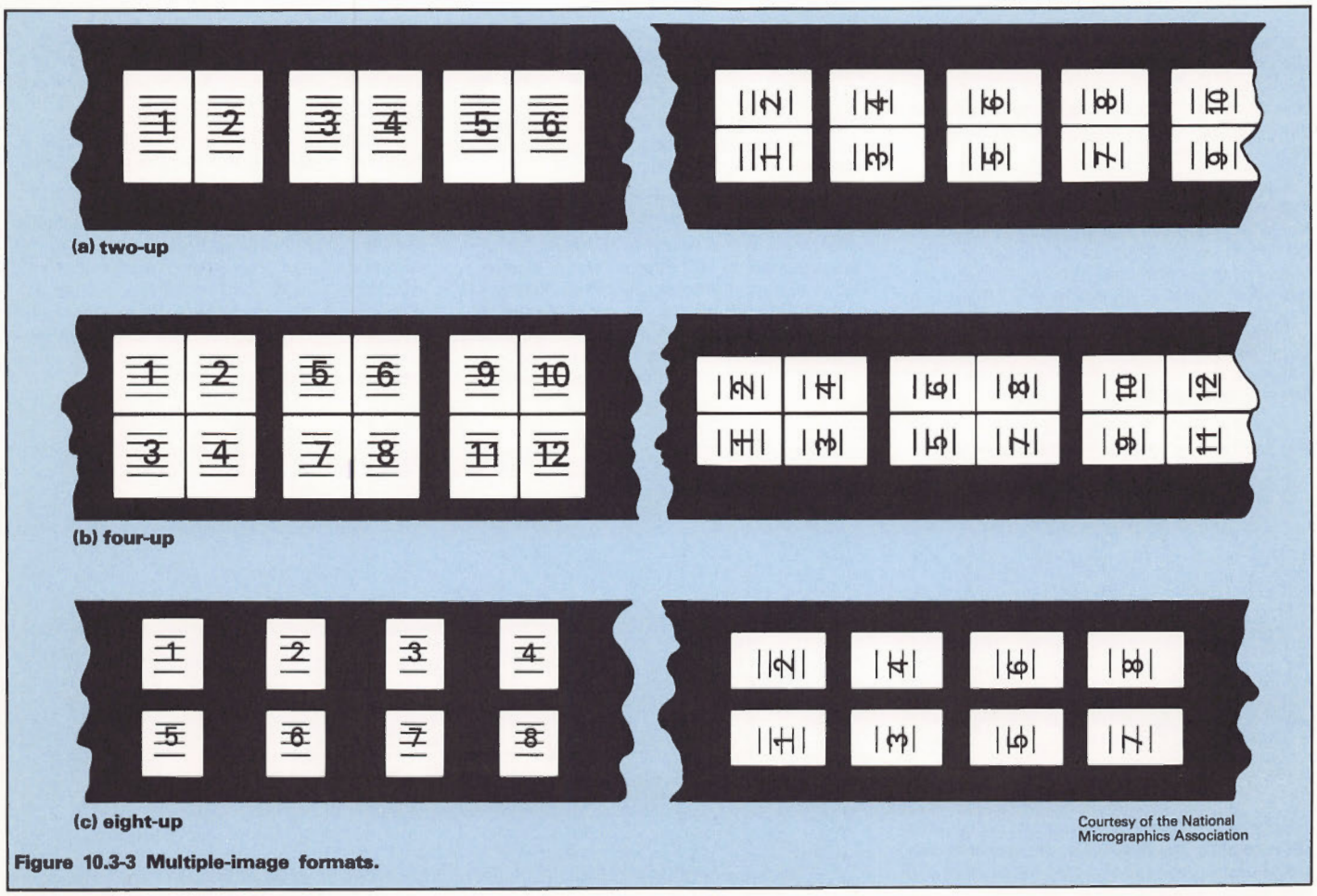
(b) ultrafiche

Figure 10.3-4 Typical microfiche and ultrafiche formats.

ARRANGED FOR	REDUCTION	COLUMNS	ROWS	NO. OF FRAMES 8½ x 11	NO. OF FRAMES 11 x 14	USE
8½ x 11″	24X	14	7	98	49*	DOCUMENTS OR COM
11 x 14″	24X	9	7	63	63	DOCUMENTS OR COM
8½ x 11″	42X	25	13	325	156*	COM
11 x 14″	42X	16	13	208	208	COM
8½ x 11″	48X	28	15	420	210*	COM
11 x 14″	48X	18	15	270	270	COM

*A SINGLE IMAGE OCCUPIES TWO FRAMES.

Figure 10.3-5 Common microfiche formats.



(a) two-up

(b) four-up

(c) eight-up

Courtesy of the National Micrographics Association

Figure 10.3-3 Multiple-image formats.

Vesicular film consists of a polyester film coating in which images are formed by small bubbles, or vesicules, that scatter light. Conventional heat processing produces a reversed-polarity image upon projection. However, a positive copy is obtained by reflected light or when the film is coated on black paper due to light reflected from the bubble areas generated by incident light.

Resolving-power measurements are useful in determining the effects on lens quality, cleanliness, focus, vibration, film characteristics, etc. in a particular system. A standard tool for determining resolving power is the N.B.S. Microcopy Resolution Test Chart.* System resolution is determined for the lens-film combination and is a function of the contrast of the test object. Resolution may be quoted for a given film. However, the ultimate system resolution depends on all components, not just the film.

A simple method of determining quality for a system uses a method described with the N.B.S. Microcopy Resolution Test Chart. It relates the height of the lower case e to the resolution of the lens-film system. Using the equation:

$$R = qr/e \quad \text{, where} \qquad \text{(eq. 10.3-2)}$$

R is the resolution required for letters, **r** is the reduction ratio, **e** is the height in millimeters of the smallest lower case e in the original, and **q** is the desired quality index. The method defines a quality index of 8 or more to produce excellent copy (characters well-defined), of 5 to produce legible copy (read without difficulty), and of 3 to produce decipherable copy.

Numbers generally require a higher quality than letters due to redundancy of information in the written work. Equation 10.3-2 can be used to relate type size of the original material to the maximum reduction ratio for a given resolving power and quality.

This method defines the camera negative image quality. Allowance must be made for resolution lost in various duplication stages to determine the quality index of a final reproduction. The average magnification ratio between individual patterns on the N.B.S. Resolving Power Test Chart is 1.12. Consequently, the quality index for a microfilm system is taken as $(1.12)^n$ times the quality index required in the final reproduction where **n** is the number of patterns lost on the test chart in the reproduction system.

*"Instructions for the use of N.B.S. Microcopy Resolution Test Chart," Photographic Research Section, M.B.S.: US COM-NBS-DC, 6th ed., July, 1962.

Cameras for microfilming generally fall into one of two classifications, planetary or rotary. The planetary camera describes a system comprising a camera head with lens, shutter, and film, a flat-bed copyboard for the document, and provisions for illuminating the document. Planetary systems frequently use 35mm film although 16mm is sometimes used. Reduction ratios are typically 8X to 36X. The camera may have an automatic exposure system for obtaining correct exposure.

The step-and-repeat camera is a planetary camera which exposes images according to a predetermined format onto the film for fiche production. The film used is 105mm, and reduction ratios are typically 10X to 24X.

The rotary camera photographs documents while they are being continuously transported in optical synchronism with the recording film. Reductions are usually from 15X to 45X though most machines only allow the selection of one or two preset speeds. Film is frequently 16mm roll film. The rotary camera is faster and easier to use than the planetary camera, but the resolution frequently is inferior to the planetary camera due to mechanical vibrations.

Camera lenses used for microphotography are high-performance components operating at wide field angles and high relative apertures. Resolving powers of 150 lines/mm may be required with reduction ratios typically 8X to 50X. To achieve high resolution, these lenses are well-corrected for coma, astigmatism, spherical aberration, and field distortion. In addition, chromatic aberration may also be minimized, especially in color microfilm systems.

It is important to control the variation of illuminance over the document exposure area. Often, unformity is desirable. However, virtually every step in a microfilm chain (camera, duplicating, and viewing) has the potential of off-axis light losses due to cosine-fourth effects, vignetting, etc. Thus, it may be desirable to compensate for off-axis camera effects by increasing the illuminance radially outward from the center of the field.

In a planetary camera, the best results are obtained when the lights are arranged as shown Figure 10.3-7. The lights must be sufficiently to the sides to avoid specular reflection from the copy board into the camera lens and must be baffled in some manner to avoid direct light to the lens. The exact number and placement of the lights depends on the desired illuminance distribution and on the light distribution from the luminaires. A typical placement might be the 45° and 60° angles shown in Figure 10.3-7. The same principles apply in a rotary camera, but exposure area here is limited to a long narrow slit.

The spectral power distribution of the light source must be properly matched to the spectral sensitivity of the film and the spectral reflectance of the materials to be copied. For film exposure to occur at some wavelength, the film must respond at that wavelength, the copy material must reflect that wavelength, and power at that wavelength must be radiated by the light source. While the spectral power distribution of the light source is of obvious importance in color systems, it is also important for black/white films. Not only must the film respond, but the rendering of various colors on the gray scale is a function of the various spectral functions.

Microform readers come in many forms depending on the type of microform to be viewed, the environment, and the needs of the user. There are several basic types of readers available.

Lap readers, as the name implies, are usually slightly larger than an average textbook. They may easily be held for viewing and afford privacy and compactness. At present, lap readers are only available for microfiche.

Portable readers are designed to fold into a compact package about the size of a portable typewriter and generally are light in weight.

Desk or stationary readers are most suitable for use at fixed locations. Stationary readers are often superior to other types of readers in terms of image quality and convenience features. These readers normally can accommodate only one person at a time with the viewing screen placed for comfortable viewing while the operator is seated.

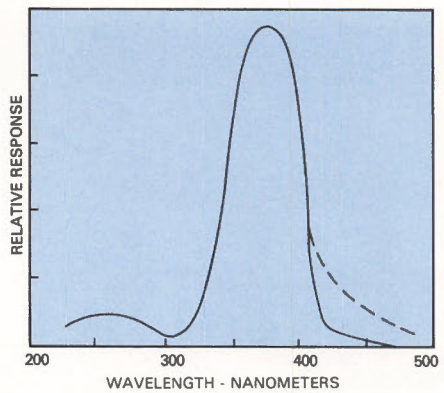


Figure 10.3-6 Spectral sensitivity of typical diazo paper. The dashed line represents the extended long-wavelength sensitivity of fast diazo paper.

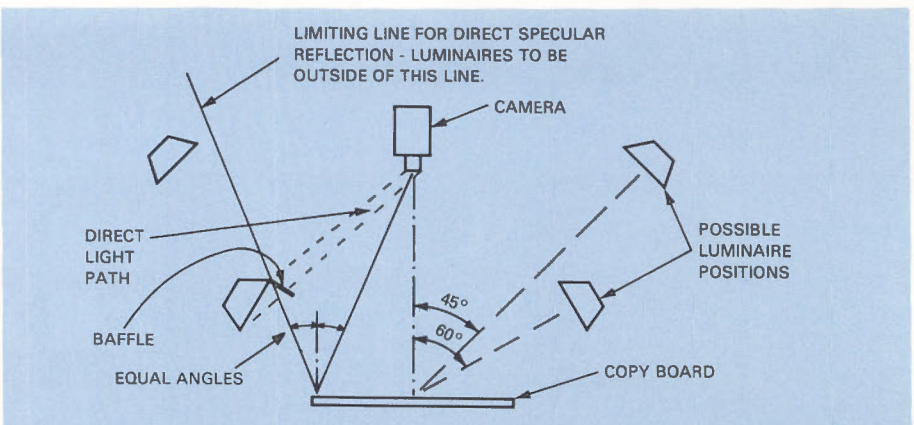


Figure 10.3-7 Arrangement of camera and luminaires for copying.

Enlarger-printers are intended strictly for printing and often do not have reading capability. Some models provide a means of previewing.

Lenses for readers and reader-printers normally have a short focal length and are designed for use at relatively high apertures and magnifications. Good image contrast is required with moderately high resolution. Figure 10.3-8 compares typical performance for microfilm camera and microfilm reader lenses.

Projection optics in microfilm viewers are basically similar to other projection systems. However, most viewers employ rear-screen systems with one or more folding mirrors between the objective and screen to minimize physical volume of the viewer. Figure 10.3-9 illustrates typical folding schemes.

Generally readers will accept either silver, diazo, or vesicular film with either positive or negative images. As a rule, the film is projected through a carrier consisting of two plates of glass or plastic called flats. This carrier is necessary due to the extremely shallow depth of focus. Fine motion control on the objective lens focuses the image, and a mechanism for moving the microform permits scanning. Some readers are designed to permit rotation of the image.

Projection screens for readers typically range from 5" x 8" to 18" x 24". Opaque front-projection screens are sometimes used, but translucent rear-projection screens are most common. Rear-projection screens may be tinted or neutral. They generally are formed by making one surface diffuse; this side appears dull as compared to the opposite shiny side. Light reflected from the screen reduces image contrast. Consequently, most screens are partially recessed or hooded to shade them from ambient light. Also, tipping the upper edge of the screen outward minimizes the effect of overhead ambient lighting. Due to the internal folding mirrors, both rearward reflected image light and ambient light multiply reflect within the housing and ultimately degrade the image contrast. The use of mirrors for reducing the size of the reader must be carefully balanced against such loss of contrast.

Uniform screen luminance from the viewer's location is an important measure of reader quality. This depends more on screen gain characteristics than on projection optics. Performance of a reader is ultimately specified in terms of screen luminance*. However, specification of the lamp and condensing system performance is best done by eliminating this highly-variable screen factor, especially since large sample-to-sample variation among screens is not uncommon. Thus, the preferred form is to specify illuminance on the rear side of the screen. For a given screen, this also determines the ultimate luminance performance due to the fixed geometric relations of the system.

*"Method for Measuring the Screen Luminance, Contrast, and Reflectance of Microform Readers," ANSI/NMA MS12-1977.

In general, readers are designed to accommodate one type of microform, although some stationary readers have provisions for accepting multiple forms. Incandescent lamps are invariably used as the projection sources. Frequently these are projection lamps, but lamps from other categories are used, e.g., compact-filament automotive types.

Another factor in considering readers is 'blowback', or the magnification factor used with the microform. It is desirable that the image magnification and reduction be nearly matched to avoid losing information. Quite often the blowback will be slightly less than the reduction. Three-quarter blowback is a common value. Many readers permit the option of changing magnification by using physically-interchangeable lenses.

Reader-printers are basically the same but have the capability of producing a hard copy of the screen image. Sensitized paper is fed from an internal container and is usually exposed by a moveable mirror which deflects the image from the viewing screen to the paper surface. A variety of photo processes can be used to make the print.

	16-MM	35-MM
FOCAL LENGTH	12.5-50MM	50-75MM
FIELD-COVERAGE (1/2 ANGLE)	15-22°	15-22°
MAGNIFICATION	UP TO 50X	UP TO 20X
RELATIVE APERTURE	*f*/2.8-*f*/5.6	*f*/2.8-*f*/5.6
RESOLVING POWER	CAPABLE OF PRODUCING SATISFACTORY 3.0 NBS CHART ON READER SCREEN.	

(a) microfilm reader lenses

	16-MM ROTARY	35-MM PLANETARY
FOCAL LENGTH	22-37MM	50-63MM
FIELD COVERAGE (1/2 ANGLE)	20°	20-26°
REDUCTION RATIOS	18X-50X	8X-36X
RELATIVE APERTURE	*f*/4-*f*/8	*f*/4-*f*/8
RESOLVING POWER (LINES/MM)	120 AT *f*/5.6	200 AT *f*/8

(b) microfilm camera lenses

Figure 10.3-8 Characteristics of typical microfilm lenses.

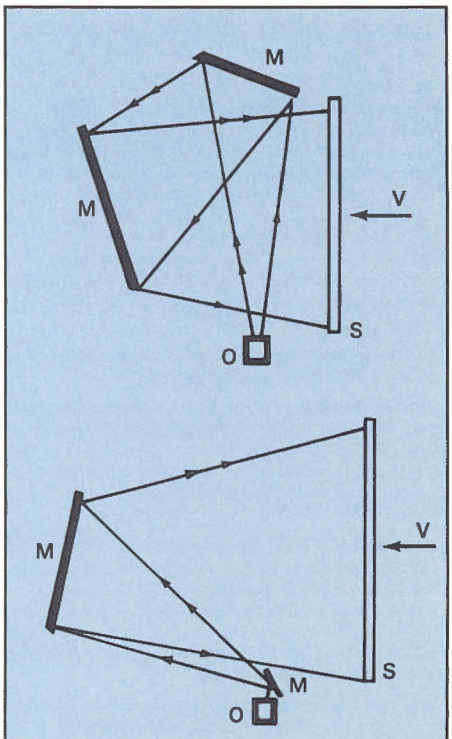


Figure 10.3-9 Typical folding schemes for microfilm readers. M, mirror; S, rear projection screen; O, objective lens; V, viewing direction.

11.0 Glossary

This glossary contains terms used in this handbook, in lamp manufacturers' literature, in lighting and in micro/photo/repro graphic applications. Terms with simple formal definitions have been so defined; terms with more complex formal definitions have been informally defined for the general reader. The definitions are based in part on the following references, the first of which (ANSI Z7.1-R1973) is especially recommended as a source of accepted definitions in lighting.

1. American National Standard Nomenclature and Definitions for Illuminating Engineering, ANSI Z7.1-R1973

2. IES Lighting Handbook, 5th ed., 1972

3. IEEE Standard Dictionary of Electrical and Electronics Terms, 2nd ed., 1977

4. The Optical Industry & Systems Directory, 23rd ed., 1972. Vol. 2

5. Sylvania Lighting Handbook for Television, Theatre and Professional Photography, 6th ed., 1977.

6. National Microfilm Association

absorptance: ratio of the flux absorbed by a medium to the incident flux. See **absorption.**

absorption: general term for the process by which incident flux that is neither reflected nor transmitted is dissipated.

absorption filter: optical filter which transmits selected wavelengths and absorbs those not transmitted. The absorbed power appears as heat, raising the temperature of the filter.

accepted quality level: level of quality determined to be practical, reasonable, and satisfactory.

achromatic: without color; i.e., having optical properties (e.g., reflection or refraction) that are invariant with wavelength, usually over the visible spectrum. An achromatic prism deviates a beam of white light without dispersing it into its constituent colors. An achromatic lens has the same focal length for all colors, and thus produces images free from color fringes. A front-surface metallized mirror is usually achromatic over a very wide spectral range. In chromaticity diagrams the achromatic region is centrally located; the white point depends on various factors; e.g., adaptation.

actinic light: light capable of causing photochemical changes in photosensitive materials.

actinic radiation: optical radiation (mainly ultraviolet and, to some extent, the shorter visible wavelengths) capable of causing photochemical effects. The actinic potential of radiation is generally proportional to photon energy and thus varies inversely with wavelength.

adaptation: process by which the sensitivity of the eye to light changes as the retina becomes accustomed to more or less light than it was exposed to during an immediately preceding period. Adaptation also refers to the final state of the process, as in **dark adaptation** or **light adaptation.** See also **scotopic vision** and **photopic vision.**

additive color mixture: color produced by combining lights of different colors, simultaneously or in rapid succession. A range of colors (determined by the choice of primaries) may be produced by combining three additive primaries (e.g., a red, a green, and a blue) in the correct proportions. See **subtractive color mixture.**

alphanumeric: pertaining to a character set that contains letters, digits, and usually other characters such as punctuation marks. Synonymous with alphameric.

American National Standards Institute (ANSI): an independent U.S. industry wide association that establishes standards to promote consistency and interchangeability among manufacturers. This organization was formerly named the United States of America Standards Institute (USASI or ASI), and previous to that the American Standards Association (ASA).

angle of collimation: angle subtended by a luminaire at a point on an irradiated surface. Also, divergence of a nearly-collimated beam from a light source.

angle of incidence: angle between a ray incident on a surface and the normal to the surface at the point of incidence. The plane formed by the incident ray and the normal is the plane of incidence.

angle of reflection: angle between a specularly reflected ray and the normal to the reflecting surface at the point of incidence. For specular surfaces, the angle of reflection equals the angle of incidence.

angle of refraction: angle between a refracted ray and the normal to the refracting surface at the point of incidence.

Ångström Å : unit of wavelength. $1\text{Å} = 10^{-10}\text{m}$. The nanometer ($1\text{nm} = 10^{-9}\text{m} = 10\text{Å}$) is now the preferred unit for wavelengths in the optical spectrum.

anode: electrode of a gaseous discharge lamp which, when it is positive, collects electrons from the discharge. See **cathode.**

ANSI: see American National Standards Institute.

antireflection coating: a coating on an optical surface which reduces the Fresnel reflectance of that surface. Antireflection coatings thus increase the transmittance of optical components.

aperture: an opening through which light or other radiation may pass. See **f-number.**

aperture card: card with a rectangular hole or holes specifically prepared for the mounting or insertion of microfilm.

aperture fluorescent lamp: lamp having most of the inside wall of the bulb (except for a narrow clear strip along the lamp) coated first with an opaque white reflective layer and then a phosphor layer. The clear strip appears as a linear source of high luminance.

aperture stop: physical element (such as a stop, diaphragm, or a lens periphery) of an optical system which limits the size of the pencil of rays traversing the system. The adjustment of the size of the aperture stop of a given system regulates the brightness of the image without having any substantial effect upon the size of the area covered.

apostilb, asb: unit of luminance equal to $1/\pi$ candela per square meter.

apparent candlepower of an extended source (at a specific distance): candlepower of a point source that would produce the same illumination at that distance.

arc discharge: electric discharge characterized by high cathode current densities (in the order of amperes per cm^2) and a low voltage drop at the cathode (comparable to the ionization potential of the gas).

arc lamp: light source which employs an arc discharge.

ASA: see **American National Standards Institute.**

ASI: see **American National Standards Institute.**

aspheric lens: lens with one or more non-spherical surfaces. These are frequently used as condensing lenses in light projection systems.

aspect ratio: ratio of width to height of a whole image, document, reproduction format, etc.

automatic focus (auto focus): feature of certain cameras or enlargers by which the image is kept in focus automatically, over some range of reduction or magnification.

average luminance (of a surface): luminance averaged over a surface for a specific direction or over a range of directions. When expressed as the total luminous flux (in lumens) leaving the surface per unit area, the average luminance of a surface (in Lambertian units) is identical to the now preferred term **luminous exitance** (q.v.).

average luminance (of a luminaire): luminous intensity at a given angle divided by the projected area of the luminaire at the angle.

background: portion of a document, drawing, microfilm, or print, which does not have line work, lettering, or other information.

back projection: see **rear screen projection.**

bactericidal (germicidal) flux: radiant flux evaluated according to its capacity to produce bactericidal effects. It usually is measured in microwatts of ultraviolet radiation weighted in accordance with its bactericidal efficiency, and is expressed in bactericidal microwatts.

ballast: device used with an electric-discharge lamp to obtain the necessary circuit conditions (voltage, current, and wave form) for starting and operating.

bare (exposed) lamp: light source with no shielding.

base: that part of a lamp to which the electrical connections are made. In many cases it also forms the mechanical support of the lamp.

base density: optical density of a film base. Since no plastic is 100% transparent, all films have some base density. The base density does not include any density produced by the emulsion layer.

base stock: carrier for a photosensitive emulsion such as paper, plastic, or cloth.

beam: cone of light from a lighting instrument.

beam angle: angle between points on a candlepower distribution curve where the candlepower is a specified per cent of maximum candlepower. Fifty per cent of maximum candlepower is the criterion used for theatrical and photographic lighting equipment; the definition varies in other applications, e.g., 10 per cent in floodlighting. See **beam spread.**

beam axis (of a projector): line midway between two lines that intersect the candlepower distribution curve at points equal to a stated per cent of its maximum (usually 50 per cent).

beam candlepower (of a projector): beam axis candlepower of a bare source that would produce the same illumination at a point if located at the same distance from the point.

beam candlepower-seconds: time integrated beam candlepower of a flash lamp and reflector combination.

beam lumens: the amount of light flux (lumens) within the beam angle of a luminaire or projector.

beam spread: (in any plane) the angle between the two directions in the plane in which the candlepower is equal to a stated per cent of the maximum candlepower in the beam.

blackbody: an ideal temperature radiator of uniform temperature whose radiant exitance in all parts of the spectrum is the maximum obtainable from any temperature radiator at the same temperature. Such a radiator is called a blackbody because it will absorb all the radiant energy that falls upon it and thus appear black. It also is called a full radiator, standard radiator, complete radiator, or ideal radiator.

blackbody (Planckian) locus: the locus of points on a chromaticity diagram representing the chromaticities of blackbodies having various temperatures.

black light: common term for near-ultraviolet radiation (i.e., in the range 320-400nm). This radiation is useful for rating lamps and their effectiveness upon fluorescent materials (excluding phosphors used in fluorescent lamps). The term does not include erythemal radiation (280-320nm) or bactericidal radiation (220-300nm).

bleed-through (show-through): undesired appearance of information from the back of a document when its front is photographed.

blended lamp: a **mercury lamp** that has been self-ballasted by a resistive filament within the **jacket.** The luminous flux is a blend of incandescent, mercury, and sometimes phosphor radiation; see **self-ballasted lamp.**

blowback: see **enlargement.**

blow-up: verb meaning to enlarge; noun meaning blowback. See **enlargement.**

blue-line print: white print with blue lines.

blueprint: blue-background print with white lines.

blue-sensitive: term applied to film and paper which are sensitive principally to blue and ultraviolet light and have little or no sensitivity to light of other wavelengths.

blurred: not sharp of distinct; any indistinct or double-outlined image is said to be blurred.

brightness: intensity of subjective sensation resulting from viewing surfaces or spaces from which light comes to the eye. This sensation is determined partly by the **luminance** of the surface and partly by conditions such as state of adaptation of the eye, background luminance, etc. See **brightness of a perceived light-source color, subjective brightness.**

brightness of a perceived light-source color: the attribute by which the source seems to emit more or less luminous flux per unit area.

bulb: transparent or translucent (e.g., glass or quartz) envelope of a lamp which encloses the active light-emitting components and materials and possible ancillary components, e.g., the filament or arc electrodes, supports, etc.

burn-in: the act of giving greater than normal exposure to all or a portion of a photosensitive material usually because of higher overall or local density in the original photomaterial being reproduced.

burn-out: over-exposure of a diazo-coated material to the point where it is incapable of coupling and producing density when developed.

camera: photographic device, employing an optical system, used for exposing light-sensitive material.

camera microfilm: first-generation microfilm; also called the 'master film'.

candela, cd: (formerly candle) the unit of luminous intensity. One candela is defined as the luminous intensity of 1/600,000 square meter of projected area of a blackbody radiator operating at the temperature of solidification of platinum under a pressure of 101,325 newtons per square meter. Values for standards having other spectral distributions are derived by the use of accepted spectral luminous efficiency data for photopic vision. Before January 1, 1948, the unit of luminous intensity in the United States was the 'international candle' which was maintained by a group of carbon-filament vacuum lamps. The difference between the candela and the old international candle is so small that only measurements of high precision are affected. Also, one lumen per steradian (1 lm/sr).

candlepower, cp.: luminous intensity expressed in candelas.

candlepower distribution curve: a curve, often polar, representing the variation of luminous intensity of a lamp or luminaire in a plane through the light center. A horizontal candlepower distribution curve represents measurements made at various angles of azimuth in a horizontal plane through the light center. A vertical candlepower distribution curve is obtained by taking measurements at various angles of elevation in a vertical plane through the light center. Unless the plane is specified for lighting fixtures, the vertical curve is assumed to represent an average such as would be obtained by rotating the lamp or luminaire about its vertical axis.

cartridge: container enclosing processed microforms, designed to be inserted into readers, reader-printers, and retrieval devices; used with a single core for roll microfilm. See **cassette.**

cassette: double-core container enclosing processed roll microfilm designed to be inserted into readers, reader-printers, and retrieval devices. See **cartridge.**

cathode: electrode of a discharge lamp which, when it is negative, supplies electrons to the discharge and also collects positive ions from the discharge.

chemical flash lamp: see **photoflash lamp.**

chip: unit of microfilm containing a micro image or images and coded identification. Chips are usually used in automatic retrieval systems and are most often 35mm in width by three inches in length or less.

chroma: parameter of the Munsell color system that corresponds most closely to saturation, and is often used as the equivalent of saturation. See **Munsell chroma.**

chromaticity: color quality of light encompassing hue and saturation. It is measured by its chromaticity coordinates or by its dominant (or complementary) wavelength and its purity.

chromaticity coordinates (of a light): generally, a pair of unique values, each lying between zero and unity, which uniquely represents the visual color of a light, including its hue and saturation. Specifically, the ratios of each of the tristimulus values of the light to the sum of the three tristimulus values. In the CIE standard colorimetric system, these coordinates are designated x, y, and z. See **chromaticity diagram.**

chromaticity diagram: a plane diagram formed by plotting one of the three chromaticity coordinates against another. See **CIE standard chromaticity diagram.**

CIE: abbreviation for Commission Internationale de l'Eclairage, the International Commission on Illumination.

CIE standard chromaticity diagram: a diagram in which the x and y chromaticity coordinates are plotted as rectangular coordinates.

cine (motion-picture) oriented images (IA orientation): jargon used with intent to reference images oriented on microfilm as follows, otherwise known as IA orientation. See **Figure 10.3-2**

clarity: readability or sharpness of detail.

code line: visual index consisting of an optical pattern of clear and opaque bars parallel with the long edge of the microfilm, located between image areas.

coefficient of beam utilization, CBU: the ratio of the luminous flux (lumens) reaching a specified area directly from a floodlight or projector to the total beam luminous flux.

coefficient of utilization, CU: ratio of the luminous flux (lumens) from a luminaire received on the workplane to the lumens emitted by the luminaire's lamps alone.

cold-cathode lamp: electric-discharge lamp whose mode of operation is that of a glow discharge, and having electrodes so spaced that most of the light comes from the positive column between them. See **glow discharge.**

cold mirror: dichroic-coated surface which reflects light but transmits infrared radiation so that the reflected beam causes less heating.

collimate: to make rays of light parallel.

color: visual sensation of a light which is dependent only on the relative spectral distribution of radiant energy in the visible part of the spectrum. See **light-source color** and **object color.**

color correction (of a photograph or printed picture): adjustment of a color reproduction process to improve the color conformity of the reproduction to the original.

color discrimination: perception of differences between two or more colors.

color matching: process of adjusting the color of one area so that it is the same color as another.

color mixture: color produced by the combination of lights of different colors. See **additive color mixture, subtractive color mixture.**

color rendering: general expression for the effect of a light source on the color appearance of objects in comparison with their color appearance under a reference light source.

color rendering index, CRI (of a light source): measure of the degree to which the perceived colors of objects illuminated by the source conform to those of the same objects illuminated by a reference source for specified conditions.

color temperature (of a light source): absolute temperature of a blackbody radiator having a chromaticity equal to that of the light source. See also **correlated color temperature** and **distribution temperature.**

colorimetric purity (of a light): ratio L_1/L_2 where L_1 is the luminance (photometric brightness) of the single frequency component that must be mixed with a reference standard to match the color of the light and L_2 is the luminance (photometric brightness) of the light. See **excitation purity.**

colorimetry: measurement of color.

COM: computer output microfilm; microfilm containing data produced by a recorder from computer-generated electrical signals.

comic-strip-oriented images (IB orientation): jargon used with intent to reference images oriented on microfilm as follows, otherwise known as IB orientation. See **Figure 10.3-2**

complementary wavelength (of a light): wavelength of light of a single frequency that matches a reference standard light when combined with a sample color in suitable proportions. Colors that have no dominant wavelengths (e.g., nonspectral violet, purple, magenta and nonspectral red) are specified in terms of their complementary wavelengths.

computer graphics: drawings, patterns, and graphs produced by a computer on paper, microfilm, or the screen of a CRT.

condenser lens: lens(es) in a projection system which directs light from the lamp through the gate or film aperture and into the projection lens.

contact paper: sensitized paper, generally low in speed, used for making prints by contact methods. See **contact print.**

contact print: print produced by exposure of the unexposed stock in immediate contact with a master or intermediate.

continuous printing: method of printing in which the roll of film being copied and a roll of paper or film are synchronized to move at a related speed over the printing aperture.

continuous-tone copy: photographic copy which contains a varying gradation of gray densities between black and white.

contrast: (1), expression of the relationship between the high and low brightnesses of a subject or between the high and low densities of a photographic image; (2), rate of density change or the density change per unit exposure. A photographic image is said to have high contrast if the difference between the maximum and minimum densities is great. Sensitized materials are graded from 'hard' (high contrast) to 'soft' in accordance with their inherent contrast characteristics.

contrast range: ratio of the highest luminance in a scene to the lowest luminance.

contrast resolution index (CR Index): measure applied to legibility determination. The relationship between background density (BD), line density (LD) and resolution (R) is expressed as: $(BD/LD) \bullet R = CR\ Index$. Where CR is above a stated value, legibility is possible.

copy: noun meaning duplicate (deprecated in that sense). The product obtained from reproducing an original. Verb meaning to reproduce an original by hand or by machine.

copy, macroscopic: copy with information large enough to be read without magnification.

corner cut: on aperture cards and microfiche, a diagonal cut at the corner of a card as a means of identifying the photosensitive side of the film.

correlated color temperature (of a light source): absolute temperature of a blackbody whose chromaticity most nearly approximates that of the light source whose chromaticity is not on the blackbody locus.

cosine law: law stating that the illumination on any surface varies as the cosine of the angle of incidence. The angle of incidence is the angle between the normal to the surface and the direction of the incident light. The inverse-square law and the cosine law can be combined to give $E = (I \cos\theta)/d^2$. See **inverse-square law.**

CRT: Cathode Ray Tube; a vacuum tube in which a gated electron beam impinges upon a surface, usually phosphor coated, resulting in a display which may be read visually or microfilmed or photographed or recorded in some other manner.

critical fusion frequency, cff: see **flicker fusion frequency.**

critical flicker frequency, cff: see **flicker fusion frequency.**

dark adaptation: process by which the retina becomes adapted to a luminance less than about 0.01 footlambert. See **light adaptation, scotopic vision.**

data storage and retrieval systems: systems having as their main function the storage of file items for later reuse rather than modification, and most often to maintain the file items unaltered, with the exception of updating and purging.

daylight filter: optical filter used to balance light from a source in order that the spectral distribution will approximate daylight; used when a camera or film balanced to daylight response is used with sources such as incandescent lamps.

definition (photo): that quality of a photo image which is associated with clarity of detail.

density: see optical density.

depth of field: distance between the points nearest and farthest from the camera which are acceptably sharp, at a given lens setting.

depth of focus: allowable tolerance in lens-to-film distance within which an acceptably sharp image of the subject focused upon can be obtained.

desk-top reader: small microfilm reader which can be placed on top of a desk and generally occupies about one square foot or less. See **reader.**

develop: to subject to the action of chemical agents or physical agents (as in xerography) for the purpose of bringing to view the invisible or latent image produced by the action of light on a sensitized surface.

diazo material: slow print film or paper, sensitized by means of diazonium salts, which after exposure (to light strong in the blue-to-ultraviolet spectrum) and development forms an image. Diazo material generally produces nonreversible images, i.e., a positive image will produce a positive image and a negative image will produce a negative image.

dichroic filter: optical filter which transmits selected wavelengths and reflects all others with low absorption. See **interference filter.**

dichroic mirror: optical filter which reflects desired wavelengths and transmits all others with low absorption. See **cold mirror, hot mirror.**

diffusion: spreading or scattering of light during reflection or transmission. In the latter case the transmission medium is said to be translucent.

dim: literally, to reduce the amount of light; in photographic, television, and theatrical lighting, to change the amount of light either by increasing it or decreasing it, viz., to dim up or to dim down.

dimensional stability: term applied to the relative ability of photographic materials to maintain their original size and shape, during and after processing, and also under various conditions of temperature and humidity.

dimmer: device used for controlling the amount of light radiated from a luminaire. Common electrical types are: resistance, autotransformer, magnetic amplifier, silicon controlled rectifier or semi-conductor, and thyratron. Mechanical devices such as iris type dimmers are also used. See **iris diaphragm.**

direct-image film: film that will retain the same polarity as the previous generation or the original material; that is, tone for tone, black for black, white for white, negative for negative, or positive for positive, with conventional procession. See **polarity.**

direct positive: see **direct-image film.**

direct reading: see **right reading.**

distribution temperature (of a light source): absolute temperature of a blackbody whose relative spectral distribution in the visible region of the spectrum approximates that of the light source.

document: written, typed, or printed paper.

document mark (blip): optical mark, usually rectangular, within the recording area, and usually below the image on a roll of microfilm. Used for counting images or frames automatically.

document retrieval system: system which provides a complete copy of the document instead of just a citation or reference.

dodging: printing technique in which certain areas being exposed are temporarily shielded, thereby producing a different exposure than that used for the rest of the print. This is essentially the opposite of **burn in.**

dominant wavelength (of a light): single wavelength of light which, when combined in suitable proportion with achromatic light from a specified reference standard, matches the color of the light under consideration. See **complementary wavelength.**

double-perforated film: roll film having sprocket holes accurately located along both edges of the film to aid in transporting and positioning frames for successive exposures in a camera.

dry process (diazo): two-component diazo process in which development is achieved without wetting, e.g., by the use of ammonia vapor.

dry silver film: non-gelatin silver film which is developed by application of heat.

duo: term used to define an image-positioning technique in rotary camera micro filming. One half of the film is masked and images are photographed along the exposed half of the film. When the full length of film has passed through the camera, it is reloaded so that a second series of images is photographed on the side previously left unexposed.

duplex: term used to define an image-positioning technique in rotary camera microfilming. Through the use of mirrors or prisms, an image of the front side of a document is photographed on one half of the film while an image of the back side of the same document is photographed simultaneously on the other half of the film.

duplicate: noun meaning, in microcopying, a copy usually made by contact printing from a master or an intermediate; verb meaning to make multiple copies of a document, usually with the aid of a master.

duplicating: to make single or multiple copies of a document or microform, usually with the aid of a master or intermediate.

efficacy: see **luminous efficacy of a source of light** and **spectral luminous efficacy of radiant flux.**

efficiency: ratio of a specifically designated output flux (lumens) to an input flux such as the flux (lumens) generated by the lamps in a luminaire; e.g., beam efficiency, field efficiency, luminaire efficiency, etc. Various utilization efficiencies involve the ratio of flux delivered to a specific location divided by the total flux input to the system.

eight-up format: 35mm microfilm format which permits eight documents, each approximately 8½ × 11 inches in size, to be filmed within a single microfilm frame.

electric discharge: see **arc discharge, gaseous discharge** and **glow discharge.**

electric-discharge lamp: lamp in which light (or radiant energy near the visible spectrum) is produced by the passage of an electric current through a vapor or a gas. See **cold-cathode lamp, hot-cathode lamp, glow lamp, fluorescent lamp, mercury lamp, fluorescent-mercury lamp.** Note: Electric-discharge lamps may be named after the filling gas or vapor that produces most of the radiation (e.g., mercury lamps, sodium lamps, neon lamps, argon lamps, etc.), the physical dimensions or operating parameters (e.g., short-arc lamps, high-pressure lamps, low-pressure lamps), or application (e.g., photochemical lamps, bactericidal lamps, blacklight lamps, sun lamps).

electrodeless discharge: gaseous discharge in which the potential differences causing the acceleration of electrons are induced by time-varying electromagnetic fields. See **gaseous discharge, electrodeless-discharge lamp.**

electrodeless-discharge lamp: lamp employing an electrodeless discharge to convert electrical energy into light.

electroluminescence: emission of light from a phosphor excited by directly impressed electric fields, which may be continuous, variable, or alternating.

electromagnetic radiation: energy propagated by means of combined oscillating electric and magnetic fields.

electromagnetic spectrum: continuum of electromagnetic radiation encompassing all wavelengths.

electronic flash: brief flash of high-intensity light generated by a pulse of current (usually from the discharge of a capacitor) through a xenon—filled flash lamp or flash tube. The equipment comprising flash lamp, reflector, power supply, and trigger circuits is called an electronic flash unit or strobe.

emittance: ratio of the radiance (for directional emittance) or radiant exitance (for hemispherical emittance) of an element of surface of a temperature radiator to that of a blackbody at the same temperature. Unless spectral emittance is specified, integration over all wavelengths is generally implied.

emulsion: single or multi-layered coating of gelatinous material on a transparent base carrying photosensitive chemicals that create a latent image upon exposure. Processing techniques produce a final, visible, useable image.

enlargement: reproduction larger than the original or the intermediate.

enlargement ratio: ratio of the linear measurement of a microimage of a document to the linear measurement of the enlarged image, expressed as 20X, 30X, etc.

envelope: see **bulb.**

erythemal flux: radiant flux evaluated according to its capacity to produce delayed erythema (as opposed to heat erythema) of the untanned human skin. It usually is measured in microwatts of ultraviolet radiation weighted in accordance with its erythemal efficiency, and is expressed in erythemal microwatts or erythemal units (q.v.).

erythemal unit, EU: unit of erythemal flux equal to the amount of radiant flux that will produce the same erythemal effect as 10 microwatts of radiant flux at 296.7nm. Also called E-viton.

etendue: see **throughput.**

E-viton: see **erythemal unit.**

excitation purity: distance between achromatic and sample points, divided by the distance between the achromatic point and a point on the spectrum locus representing the dominant wavelength of the sample. See **colorimetric purity.**

exitance: flux leaving a surface per unit area. See **luminous exitance** and **radiant exitance.**

exposures: (1), act of exposing a light-sensitive material to a light source; (2), section of a film containing an individual image, as a roll containing six exposures; (3) time during which a sensitive surface is exposed, as an exposure of two seconds; (4), product of light intensity and the time during which it acts on the photosensitive material.

exposure index: see **film speed.**

facsimile: , exact copy of an original document; (2), process or result of the process by which fixed graphic images are scanned, transmitted electronically, and reproduced either locally or remotely.

fading: (1), loss in density of photographic images; (2), degradation of photographic images; (3), in lighting, to dim.

fast: (1), having high photographic speed. The term may be applied to a photographic process as a whole, or it may refer to any element in such a process, such as the optical system, the emulsion, or a developer. (2), resistance to the action of destructive agents, i.e., a latent image may be fast to light, fast to heat, or fast to diffusion.

fiber optics: technique and devices for transmitting light through long flexible fibers of glass or plastic by repeated total internal reflections.

fiche: see **microfiche.**

field: area covered or 'seen' by the lens of a camera.

film: any sheet or strip of transparent plastic coated with a light-sensitive emulsion.

film, nonperforated: roll film which does not have sprocket holes or perforations.

film, nonreversing (direct positive): film which does not change from positive to negative images or vice versa in successive generations, e.g., diazo film.

film, orthochromatic (ortho): black-and-white film coated with an emulsion which is sensitive to ultraviolet, violet, blue, and green radiation. Not being sensitive to red, red objects photographed with orthochromatic film are rendered dark on a print.

film, panchromatic (pan): black-and-white film coated with an emulsion which is sensitive to the visual spectrum. The spectral sensitivities of panchromatic films approach that of the human eye.

film, perforated: roll film having sprocket holes accurately located along one or both edges to aid in transporting and positioning the film for successive exposures in a camera.

film, print: film copy reproduced usually by contact from another film.

film, processed: film which has been exposed to suitable radiation and has been treated to produce a fixed or stabilized visible image.

film, reversal: film which after exposure is specially processed to produce a positive image instead of the customary negative image.

film, roll: flexible film, wound on a reel, spool, or core.

film, safety: film which does not readily support combustion.

film, sheet: precut rectangle (not in roll form) of flexible transparent base material coated with a photosensitive emulsion.

film, silver: film which is coated with a silver-halide emulsion.

film size: film width, generally expressed in millimeters, e.g., 16mm.

film speed: numerical rating of the sensitivity of film in accordance with a standardized method of measurement. In the U. S., film speeds have ANSI (formerly ASA) ratings; in Europe, DIN (Deutsche Industrie Norme) ratings are used.

film strip: short strip of processed photographic film, usually 16 or 35mm, containing a number of frames. (As opposed to a roll, aperture card, or microfiche.)

filter: see **optical filter.**

first-generation image: picture of a document, generally used as a master, produced directly by the camera.

fixing: photographic processing which dissolves the undeveloped silver halides from a processed film or print to render the developed image more permanent.

fixture: see **luminaire.**

flare: non-image-forming scattered light which results from reflections at optical surfaces, the walls of the camera, or imperfections in the optical parts. If it reaches the image plane it produces density in the exposed area which degrades the photographic quality of the resulting record.

flash: light pulse of short duration, usually less than one second.

flash bulb: generally a **chemical flash lamp.**

flash lamp: if not specified, may be applied to either a **chemical flash lamp** or an **electronic flash** lamp.

flash tube: generally an **electronic flash** lamp.

flicker fusion frequency, fff: frequency of intermittent stimulation of the eye at which flicker disappears. Also called **critical fusion frequency (cff)** or **critical flicker frequency (cff).**

flicker index: measure of cyclic variation for light output of a lamp at a given power frequency. Determined over one cycle, it is the area under the curve but above the average value of the curve, divided by the total area under the curve.

floodlight: luminaire designed for lighting a scene or object to a luminance considerably greater than its surroundings.

floodlighting: system designed for lighting a scene or object to a luminance greater than its surroundings.

fluorescence: emission of light (luminescence) as the result of, and only during, the absorption of radiation of other (usually shorter) wavelengths.

fluorescent lamp: low-pressure mercury-discharge lamp in which a fluorescing coating (phosphor) transforms some of the ultraviolet energy generated by the discharge into light. See **instant-start fluorescent lamp, preheat (switch-start) fluorescent lamp, rapid-start fluorescent lamp.**

fluorescent-mercury lamp: electric-discharge lamp comprising a high-pressure mercury arc tube in a jacket coated with a fluorescing substance (phosphor) that transforms some of the ultraviolet energy generated by the arc into light.

flux: rate of flow of electromagnetic energy. See **luminous flux, radiant flux.**

f-number: ratio of focal length of a lens to the diameter of its entrance pupil. This measure of the light-transmitting ability of a camera lens or projection lens is also called **lens speed, lens aperture,** or **f-stop.** The amount of light transmitted by the lens varies inversely as the square of the f-number. Note that the f-number does not take into account losses in the lens. See **t-number.**

focal length: distance between a principal point of a lens or reflector and the focal point. For simple lenses in luminaires this distance is frequently measured from the center of the lens to the focal point.

focal point: the small region where a lens or reflector concentrates most light rays received from a distant source of light.

focus: in addition to its optical meanings, focus is used as a verb to indicate the aiming and adjusting of a luminaire.

fog: non-image photographic density. The defect is due to the action of stray light, improperly compounded processing solutions, or wrongly stored or outdated photographic materials.

footcandle, fc: unit of illuminance equal to one lumen per square foot (1 lm/ft²). The illuminance on a surface one square foot in area on which there is a uniformly distributed flux of one lumen, or the illuminance on a surface all points of which are at a distance of one foot from a directionally uniform point source of one candela.

footlambert, fL: unit of luminance equal to $1/\pi$ candela per square foot ($1/\pi$ cd/ft²). The uniform luminance of a perfectly diffusing surface either emitting or reflecting light at the rate of one lumen per square foot. The luminance of a perfectly diffusing reflecting surface in footlamberts is, therefore, the product of the illumination in footcandles by the luminous reflectance of the surface. This is a deprecated unit. See **luminance.**

frame (film frame): area of a photographic film exposed to light in a camera during one exposure, regardless of whether or not this area is filled by the document image.

frame, microfiche: (1), one microimage and margin contained within a film frame; (2), single area of a grid pattern.

Fresnel lens: lens that acts similarly to a plano-convex lens but is thinner and lighter due to steps on the convex side. Often in theatrical applications the flat side has a rough surface to smooth light beams by slightly diffusing the light.

Fresnel reflection: reflection of a portion of the light incident on the surface separating two media having different indices of refraction.

front-surface mirror: mirror having reflective coating applied to the front surface instead of the back. Also called first-surface mirror.

f-stop: see **f-number.**

fuzzy: appearance of an image that lacks sharpness.

gaseous discharge: conduction of electricity in a gas when molecules of that gas become ionized by collisions with electrons accelerated by potential differences across the gas.

gate, film: aperture unit in a camera, printer, or reader in which the film is held at a fixed relationship to a lens.

general lighting: lighting designed to provide a substantially uniform level of illumination throughout an area, exclusive of provisions for special local requirements.

generation: measure of the remoteness of a particular copy from the original material. The picture taken of a document, cathode ray tube, etc. is termed first-generation microfilm (camera microfilm). Copies made from this first generation are second generation, copies made from the second generation are third generation, etc. First-generation negative-appearing microfilm is designated 1N and second-generation positive-appearing microfilm is designated 2P, etc. See **N, P, negative-appearing image, positive-appearing image.**

generation, even: second, fourth, sixth, etc. generations.

generation, odd: first, third, fifth, etc. generations.

germicidal flux: see **bactericidal flux.**

glare: sensation produced by luminances within the visual field that are sufficiently greater than the luminance to which the eyes are adapted to cause annoyance, discomfort, or loss in visual performance and visibility. The magnitude of the sensation of glare depends upon such factors as the size, position and luminance of a source, the number of sources, and the luminance to which the eyes are adapted.

glow discharge: electric discharge characterized by an approximately constant low current density (in the order of mA/cm²) at the cathode, low cathode temperature, and an approximately constant high voltage drop (5-10 times the ionization potential of the gas).

glow lamp: electric-discharge lamp which operates in the glow-discharge mode, and in which light is generated in the space close to the electrodes.

graininess: subjective impression of nonuniformity in an area of a photograph corresponding to uniform exposure most often noticeable in enlargements with a magnification of ten or more.

graybody: temperature radiator whose spectral emissivity is less than unity and the same at all wavelengths.

grid, microfiche: defined array of horizontal and vertical lines which divide an area into uniform spaces called frames. The grid defines the arrangement of the rows and columns of microimages.

gross density: total density of film including base density, image density and fog.

halation: halo ghost image or fog caused by reflection of rays of light from the base to the emulsion or by internal scattering of light within the film.

halftone: reproduction of a photograph in which the gradation of tone is reproduced by various size dots and intermittent white spaces. It is produced by interposing a screen between the lens and the film.

halide: any compound of chlorine, iodine, bromine, or fluorine, and another element. Silver bromide, silver chloride, and silver iodide are the light-sensitive materials in silver emulsions.

hand viewer: small, portable magnifying device used for viewing microfilm. Magnification generally ranges from 5X to 15X.

hard: photographic film or paper which has high contrast, or developer which produces high contrast.

hard copy: enlarged copy, usually on paper.

hard glass: glass having an intermediate coefficient of thermal expansion ($30\text{-}60 \times 10^{-7}\,°C^{-1}$), and a softening temperature on the order of 700°C. See **soft glass.**

hard-glass halogen lamp: tungsten-halogen lamp with a bulb of hard glass instead of fused silica or high-silica glass. Hard-glass fabrication techniques generally permit lower costs than for other tungsten-halogen lamps having equivalent performance, but are usually limited to low-voltage, low-wattage types.

heat filter: optical filter which transmits light and either absorbs or reflects infrared in order to reduce heating effects of the light beam.

HID lamp: see **high-intensity discharge lamp.**

high-intensity discharge (HID) lamp: one of a general group of lamps consisting of mercury, metal halide, and high-pressure sodium (HPS) lamps.

high-output (HO) fluorescent lamp: one designed to operate at loadings of about 14 watts per foot, as compared with typical loadings of 10 watts per foot for standard fluorescent lamps.

high-pressure sodium (HPS) lamp: high-intensity discharge lamp in which the major portion of the radiation is produced by the excitation of sodium vapor at a pressure in the order of 0.1 atmospheres.

high reduction (hr): reduction above 30X up to and inclusive of 60X.

hot-cathode lamp: electric-discharge lamp operating in the arc-discharge mode. The cathodes may be heated by the discharge itself or by external means.

hot mirror: dichroic-coated surface which transmits light but reflects infrared so that the transmitted beam causes less heating.

hue: attribute of a light source or object that determines whether it is perceived as red, orange, yellow, green, blue or violet, without regard to the other aspects such as saturation and brightness. See **Munsell hue.**

IES: see **Illuminating Engineering Society.**

illuminance: luminous flux incident per unit area on a surface. The quantitative level of illumination on a surface. See **illumination.**

illuminant: source of radiation having a specified spectral power distribution.

illumination: used in a qualitative or general sense to designate the act of illuminating or the state of being illuminated. Illumination also has the quantitative meaning of **illuminance,** but this use is deprecated.

Illuminating Engineering Society: professional organization of engineers, architects, designers, contractors, distributors, utility personnel, manufacturers, and scientists concerned with any aspect of lighting.

image, latent: invisible image produced by the action of radiant energy on a photosensitive surface. It may be made visible by the process of development.

image, negative: photographic image in which the values of light and dark of the original subject are inverted. In a negative, light objects are represented by high densities and dark objects are represented by low densities.

image, positive: photographic image in which the values of light and dark of the original subject are represented in their natural order. In a positive, light objects are represented by low densities and dark objects are represented by high densities.

image, real: in optics, an image which actually exists and could be thrown on a screen at the position where it appears to be.

image, virtual: in optics, an image whose existence and properties are inferred by tracing various rays of light backward, into or beyond some lens or mirror surface. A virtual image does not exist at the location where it appears to be; however, the rays of light which appear to come from the virtual image behave in the same way that they would behave if they came from a real image having the location of the virtual image and in the absence of any interfering optical surfaces.

incandescence: self-emission of radiant energy in the visible spectrum resulting from the thermal excitation of atoms or molecules in a solid or a liquid.

incandescent-filament lamp: lamp in which light is produced by a filament heated to incandescence by an electric current.

index of refraction (of a transmitting medium): ratio of the velocity of light in air or vacuum to the velocity of light in the medium. The index of refraction usually varies with wavelength.

information: any facts or data which can be used, transferred, or communicated.

information area: area of a document which contains information; usually exclusive of the margin.

infrared radiation: radiant energy in the wavelength range 780 nm to 10^6nm.

initial lumens: rated lumens of a light source. These values are determined after a short seasoning period dependent on lamp type; e.g., fluorescent lamps are rated at 100 hours. See **seasoning.**

initial luminous exitance: density of luminous flux leaving a surface within an enclosure before interreflections occur. For light sources, this is the luminous exitance as defined in **luminous flux density at a surface** (q.v.). For non-self-luminous surfaces it is the reflected luminous exitance of the flux received directly from sources.

instant-start fluorescent lamp: fluorescent lamp designed for starting by a high voltage without preheating of the electrodes.

intensity (of a source): flux leaving the source per unit solid angle in a specific direction. See **candela, candlepower, luminous intensity, radiant intensity.**

intensity distribution: polar or rectangular plot of source intensity versus direction.

interference: phenomenon in which the resultant of two or more superimposed waves may be of larger magnitude than any individual wave (constructive interference) or of smaller magnitude (destructive interference).

interference filter: optical filter employing interference phenomena in multiple layers of thin metal and/or dielectric films to achieve selective spectral transmission or reflection.

internal reflector (lamp): focusing reflector (usually paraboloidal or ellipsoidal) within a projection lamp. See **proximity reflector.**

inverse-square law: law stating that the irradiance or illuminance from a point source varies directly with the intensity of the point source and inversely as the square of the distance from the source. For sources of finite size, the error depends on subtended source angle and luminance distribution of the source. For luminaires the error usually does not exceed a few per cent when the distance from the source is at least five times the maximum dimension of the source (or luminaire). See **cosine law.**

iris diaphragm: mechanical device for varying the diameter of a circular aperture and used to control the flux through the aperture.

irradiance: radiant flux incident per unit area on a surface.

irradiation: the act of causing radiant flux to fall on a surface.

isocandela line: one plotted on any appropriate coordinates to show directions in space, about a source of light, in which the candlepower is the same. For a complete exploration the line always is a closed curve. A series of such curves is called an isocandela diagram. See **isolux line.**

isolux (isofootcandle) line: one plotted on any appropriate coordinates to show all the points on a surface where the illuminance is the same. For a complete exploration the line is a closed curve. A series of such lines for various illumination values is called an isolux (isofootcandle) diagram. See **isocandela line.**

jacket: transparent or translucent outer envelope in which light sources (e.g., arc tubes) are sometimes enclosed.

kelvin,K: unit of temperature equal in magnitude to 1°C, but based on an absolute temperature scale in which 0K = -273.15°C, 273.15K = 0°C, 373.15K = 100°C, etc. Note that absolute temperatures are written without degree (°) signs, and are read as zero kelvins, 273 kelvins, 373 kelvins, etc. Light source color temperatures are expressed in kelvins.

lambert, L: unit of **luminance** (q.v) equal to $1/\pi$ candela per square centimeter ($1/\pi$ cd/cm²). The uniform luminance of a perfectly diffusing surface either emitting or reflecting light at the rate of one lumen per square centimeter. Also the average luminance of any surface emitting or reflecting light at the rate of one lumen per square centimeter. For the general case, the average must take account of variation of luminance with angle of observation and also of its variation from point to point on the surface considered.

Lambert's cosine law: law stating that the intensity in any direction from a perfectly diffusing surface varies as the cosine of the angle between that direction and the normal to the surface.

Lambertian surface: surface that emits or reflects light in accordance with Lambert's cosine law; a perfectly diffusing surface. A Lambert surface has the same luminance regardless of viewing angle.

lamp: general term for a man-made source of light and/or radiation in regions of the spectrum adjacent to the visible. A lighting unit consisting of a lamp with shade, reflector, enclosing globe, housing, or other accessories is also called a 'lamp.' In such cases, in order to distinguish between the assembled unit and the light source within it, the latter is often called a 'bulb' or 'tube.' See also **luminaire.**

lap reader: microfilm reader less than 4kg. in mass (less than 8.8 lbs.). See **reader.**

latitude: term indicating the range of exposures over which a sensitized material will yield an acceptable reproduction. It is usually related to the length and slope of the straight-line portion of the characteristic curve.

leader: film at the beginning of a roll which is used for the threading of a camera, projector, or processing machine.

lens aperture: see **f-number.**

lens speed: see **f-number.**

LCL: see **light center length.**

light: electromagnetic radiation detectable by the human eye; visually-evaluated radiant energy in the spectral range 380 to 780 nm. See **photopic vision, scotopic vision, spectral luminous efficiency of radiant flux.**

light adaptation: process by which the retina becomes adapted to a luminance greater than about one footlambert. See also **dark adaptation, photopic vision.**

light box: device for inspecting film, which provides diffused illumination evenly dispersed over the viewing area.

light center (of a lamp): center of the smallest sphere that would completely contain the light-emitting element of the lamp.

light center length, LCL (of a lamp): distance from the light center to a specified reference point on the lamp.

light-source color: color of light emitted by the source. The color of a point source may be defined by its luminous intensity and chromaticity coordinates; the color of an extended source may be defined by its luminance and chromaticity coordinates. See **perceived light-source color.**

light-sensitive: materials which undergo changes when exposed to light. The commonly-used photographic light-sensitive materials in films and papers are the silver halides, diazo dyes, bichromated gelatin, and the photoconductive materials used in xerography.

lightness of a perceived object color: the attribute by which it seems to transmit or reflect a greater or lesser fraction of the incident light.

line copy: document consisting essentially of two tones (such as black and white or brown and buff) without intermediate tones.

low-pressure sodium lamp: lamp in which the major portion of the radiation is produced by excitation of sodium vapor at a pressure of 1-5 X 10^{-6}atmosphere. Radiation is essentially from the 589.0nm and the 589.6nm resonance lines.

low reduction (lr): reduction up to and inclusive of 15X.

LPW: see **lumens per watt, luminous efficacy.**

lumen, lm: unit of luminous flux equal to the luminous flux emitted per unit solid angle by a uniform

point source of one candela, or to the flux on a unit surface all points of which are at unit distance from a uniform point source of one candela. See **candela.**

lumen-second, lm-sec: unit of luminous energy; the quantity of light delivered in one second by a luminous flux of one lumen. Used in flash photography.

lumens per watt, lm/w or LPW: unit of **luminous efficacy** (q.v.).

luminaire: lighting unit comprising a lamp or lamps and the parts designed to distribute the light, to position and protect the lamps,and to connect the lamps to the power supply.

luminaire efficiency: ratio of luminous flux (lumens) emitted by a luminaire to that emitted by the lamp or lamps in the luminaire.

luminance: luminous flux per unit solid angle and per unit area measured normal to the direction of propagation of the flux. Also the luminous intensity of any surface (of a source, a receiver, or any other real or virtual surface) in a given direction per unit area of the surface as viewed from that direction. Previously called photometric brightness. Units are **apostilb,** candela per unit area, **footlambert, lambert, nit,** and **stilb.**

luminance contrast: relationship between the luminances of an object and of its immediate background. It is equal to $(L_1 - L_2)/L_1$ or $(L_2 - L_1)/L_1$, where L_1 and L_2 are the luminances of the background and object, respectively. The form of the equation must be specified. Because of the relationship among luminance, illumination, and reflectance, contrast often is expressed in terms of reflectance when only reflecting surfaces are involved. Thus, contrast is equal to $(P_1 - P_2)/P_2$ or $(P_2 - P_1)/P_1$ where P_1 and P_2 are the reflectances of the background and object respectively. This method of computing contrast holds only for perfectly diffusing surfaces; for other surfaces it is only an approximation unless the angles of incidence and view are taken into consideration. See **reflectance.**

luminance (brightness) coefficient: coefficient similar to the coefficient of utilization used to determine wall and ceiling luminances.

luminance difference: difference in luminance between two areas. It usually is applied to contiguous areas, such as the detail of a visual task and its immediate background, in which case it is quantitatively equal to the numerator in the formula for **luminance contrast.**

luminance factor: ratio of the luminance of a surface or medium under specified conditions of incidence, observation, and light source, to the luminance of a perfectly reflecting or transmitting, perfectly diffusing surface or medium under the same conditions. Note: Reflectance or transmittance cannot exceed unity, but luminance factor may have any value from zero to values approaching infinity.

luminance ratio: ratio of the luminances of two areas in the visual field.

luminescence: emission of light not ascribable directly to incandescence. See **electroluminescence, fluorescence, phosphorescence.**

luminosity factor: previously used term for **spectral luminous efficacy** of radiant flux.

luminous: generally, a descriptive term for an element emitting light or for radiant quantities in the visible spectrum. Specifically, radiant quantities evaluated in accordance with the spectral luminous efficiency curve, $V(\lambda)$.

luminosity curve: plot of **spectral luminous efficiency** function $V(\lambda)$ versus wavelength.

luminous density: quantity of light (luminous energy) per unit volume.

luminous efficacy of radiant flux: ratio of total luminous flux to total radiant flux. Units are lumens per watt (lm/W or LPW).

luminous efficacy of a source of light: ratio of total luminous flux emitted by the lamp to total lamp power input. Units are lumens per watt (lm/W or LPW). The term **luminous efficiency** was in the past extensively used for this concept.

luminous efficiency: see **spectral luminous efficiency** of radiant flux.

luminous emittance: see **luminous exitance.**

luminous energy: quantity of light; radiant energy evaluated in accordance with the **spectral luminous efficiency** function $V(\lambda)$. Units are lumen-seconds or lumen-hours.

luminous exitance: density of luminous flux leaving a surface without regard to direction, expressed in lumens per unit area of the surface. Formerly called **luminous emittance.**

luminous flux: rate of flow of light; radiant flux evaluated in accordance with the **spectral luminous efficiency** function $V(\lambda)$. Units are lumens (lm).

luminous flux density at a surface: luminous flux per unit area of the surface. Density of luminous flux leaving a surface is now called **luminous exitance** (q.v.); the former term **luminous emittance** is no longer used. Density of luminous flux incident on a surface is called **illuminance.**

luminous intensity:luminous flux from a source per unit solid angle in a given direction. Units are candela (cd) or lumens per steradian (lm/sr). See **intensity.**

lux, lx: unit of illuminance equal to one lumen per square meter. It is the illuminance on a surface one square meter in area on which there is a uniformly distributed flux of one lumen.

macroscopic: large enough to be read without magnification, e.g. titles on microfiche.

magnification: ratio of the size of the image of an object to the size of the object when viewed through or projected by an optical instrument. Lateral magnification is the ratio of the linear dimensions of the image and object. Angular magnification is the ratio of the angle subtended by the image seen through an optical device to the angle subtended by the object seen by the eye.

magnification range: lineal range or span of magnification in a given optical system which is usually expressed in diameters or times, i.e., magnification range 12X through 24X.

mask: (1), opaque material used to prevent exposure of certain areas, usually the border of a picture; (2), any material used to provide a border of desired color, white, or black around an image.

master: copy of a document, or (in some processes) the original itself from which copies can be made.

matte surface: one from which the reflection is predominantly diffuse, with a negligible specular component; one that reflects light uniformly in all directions.

maximum overall length (MOL): maximum dimension of a lamp; from base to base for double-ended lamps, or from extreme point of base to extreme point of bulb for single-ended lamps.

mean spherical candlepower: **see mean spherical intensity.**

mean spherical intensity: the luminous intensity of a source averaged over the total solid angle about the source; total luminous flux divided by 4π.

medium reduction (mr): reduction above 15X up to and inclusive of 30X.

mercury lamp: high-intensity discharge lamp in which the major portion of the radiation is produced by the excitation of mercury atoms.

mesopic vision: the transition region between those of **photopic vision** and **scotopic vision.**

metal-halide lamp: high-intensity discharge lamp in which the light is produced by the radiation from a mixture of mercury and a metallic vapor resulting from the dissociation of one or more metal halides (e.g., halides of scandium, thallium, indium, or sodium.)

metamers: colors perceived to be identical, but which have different spectral power distributions.

metameric match: visual equivalence of two or more metamers. Two objects of different spectral characteristics are metameric matches if their colors are perceived to be identical when they are illuminated by the same source.

microcopy: copy obtained by photography in a size too small to be read without magnification.

microfiche: sheet of microfilm containing multiple microimages in a grid pattern. It usually contains a title which can be read without magnification.

microfilm: fine-grain, high-resolution film containing an image greatly reduced in size from the original.

microform: generic term for any form, either film or paper, which contains microimages.

micrographics: the industry which reduces any form of information to a microform medium. See **microform.**

microimage: unit of information, such as a page of text or a drawing, too small to be read without magnification.

micrometer,μm: unit of length equal to 10^{-6} meter. Formerly called micron,μ.

micron,μ: see **micrometer.**

microprint: microimages produced by printing on opaque stock, as distinct from microimages produced on a photosensitive material.

microreproduction: (1), copy rendered in sizes too small to be read without magnification and which is produced photographically or by other means on either transparent or opaque materials; (2), process of making microimages.

mired: measure of reciprocal color temperature, used to express color differences near the Planckian blackbody locus. (1 mired = 10^6/color temperature, in K). One mired varies from about 4K at 2000K to 100K at 10,000K.

mirror image: see **reverse reading.**

MOL: see **maximum overall length.**

Munsell chroma, C: index of saturation of perceived object color defined in terms of the Y-value and chromaticity coordinates (x, y) of the color of light reflected or transmitted by the object.

Munsell color system: system of surface-color specification based on perceptually uniform color scales for the three variables: **Munsell hue, Munsell value,** and **Munsell chroma.** For an observer of normal color vision, adapted to daylight, and surrounded with a middle gray to white background, the Munsell hue, value, and chroma of the color correlate well with the hue, lightness, and saturation of the perceived color.

Munsell hue, H: index of the hue of perceived object color defined in terms of the Y-value and chromaticity coordinates (x, y) of the color of the light reflected or transmitted by the object.

Munsell value, V: index of the lightness of perceived object color defined in terms of the Y-value. Munsell value is approximately equal to the square root of the reflectance expressed in per cent.

N: symbol of negative-appearing microfilm. See **generation, negative-appearing image.**

nanometer, nm: unit of length. 1nm = 10^{-9}m. Formerly called millimicron, mμ.

negative-appearing image: photographic image with light lines, characters, and neutral tones on a dark background.

neutral-density filter: optical filter that attenuates light without changing its relative spectral distribution.

nigrescence time: time for the light output of a lamp to decay to a given percentage after turn-off.

nit, nt: unit of luminance equal to one candela per square meter.

object color: color of the light reflected or transmitted by an object when illuminated by a specified light source, frequently a standard light source such as CIE source A, B, C, or D65. See **standard source** and **perceived object color.**

objective lens: in cameras, microscopes and telescopes, the optical element(s) nearest the object.

opacity: reciprocal of **transmittance.**

opal glass: white or near-white translucent glass used to diffuse light.

opaque projector: optical instrument that projects images of opaque objects such as printed material.

opaque screen: reader screen of opaque material on which an image is produced by reflected light.

optical density (D): $\log_{10}$ (1/transmittance). See **opacity.**

optical filter: optical component that selectively transmits desired wavelengths and reflects or absorbs other wavelengths.

optical print: microfilm print made by projection, not by contact; the print may be the same size, enlarged, or reduced. See **projection printing.**

optical radiation: electromagnetic radiation in the ultraviolet, visible, and infrared regions of the spectrum that obeys the laws of optics.

optical system: (1), combination of lenses and/or reflectors designed to perform any desired optical function; (2), all the parts of a photographic lens and accessory optical elements designed to form images of objects.

original: document from which copies are produced.

ozone-producing radiation: ultraviolet energy shorter than about 220 nanometers that decomposes oxygen(O_2) thereby producing ozone(O_3). Some ultraviolet sources generate energy at 184.9 nanometers that is particularly effective in producing ozone.

overexpose: to permit too much exposure of a photographic copy. This may be caused by light too brilliant, aperture too large, or exposure time too long.

P: symbol for positive-appearing microfilm. See **generation, positive-appearing image.**

PAR lamp: internally reflectorized tungsten filament incandescent lamp with bulb constructed from two molded glass parts, the lens or faceplate and the reflector, which are fused together at the rim. Available in a range of distributions from narrow spot to wide flood. PAR is an acronym for Parabolic Aluminized Reflector.

PAR light: luminaire using a PAR lamp. The beam characteristics depend on the PAR lamp used.

parallax: apparent displacement of an object as seen from different points. It is commonly encountered in photography as the difference in position of the image seen in the viewfinder from that actually taken by the lens.

peak sensitivity: wavelength of light which provides the most efficient response of a light-sensitive layer.

perceived light-source color: color perceived to belong to a light source.

perceived object color: the color perceived to belong to an object, resulting from characteristics of the object, of the incident light, and of the surround, the viewing direction, and observer adaptation. **See object color.**

perfect diffusion: scattering of flux in accordance with **Lambert's cosine law.**

phosphorescence: emission of light (luminescence) as the result of the absorption of radiation, and continuing for a noticeable length of time after excitation.

phot, ph: unit of illumination equal to one lumen per square centimeter (1ph = 1 lm/cm²).

photochemical radiation: optical radiation capable of producing chemical changes in materials, and thus used in photochemical processes such as accelerated fading tests, photography, photoreproduction, and chemical manufacturing. See **actinic radiation.**

photocopy: photographic reproduction, excluding microcopy, generally produced by exposing the image of an original or photographic film or paper.

photocopying: application of photographic processes to produce copies, excluding microcopies, generally by exposing the image of an original on photographic film or paper.

photoflash lamp: lamp in which combustible metal or other solid material is burned in an oxidizing atmosphere to produce light of high intensity and short duration for photographic purposes.

photograph: (1), positive or negative picture obtained by the photographic process involving exposure of a sensitized photographic material in a camera and subsequent processing and printing operations; (2), any image recorded on photographic sensitized material.

photometer: instrument for measuring photometric quantities such as luminance, luminous intensity, luminous flux, and illuminance.

photometric brightness: see **luminance.**

photometry: measurement of quantities associated with light.

photometric quantities: see **luminous.**

photopic vision: vision by means of the retinal cones. It is generally associated with adaptation to luminances of one footlambert or more. See **scotopic vision, light adaptation.**

photopolymerization: photochemical process for converting monomers into polymers by exposure to **actinic radiation.** Also, the production of images by polymerization of one or more monomers when exposed to **actinic radiation.**

Planck radiation law: expression representing the spectral radiance of a blackbody as a function of wavelength and temperature.

polarity: In reprographics, a word used to indicate the change or retention of the light to dark relationship of an image.

polarization: restriction of the electric magnetic field vectors of electromagnetic radiation to vibrations in single planes. Polarization may be plane, circular, or elliptical.

polarized light: light in which the electric and magnetic field vectors exist only in single planes at a given wavelength.

positive-appearing image: photographic image with dark lines, character, and neutral tones on a light background.

preheat (switch-start) fluorescent lamp: fluorescent lamp designed for operation in a circuit requiring a manual or automatic starting switch to preheat the electrodes in order to start the arc.

primary: any one of three lights in terms of which a color is specified by giving the amounts required to duplicate it by additive combination. See **tristimulus values of a light, X, Y, Z.**

print: noun meaning a reproduction or copy on photographic film or paper; verb meaning to produce a reproduction or copy on photographic film or paper.

print film: fine-grain, high-resolution film used primarily for making contact film copies.

printing speed: rate at which a light-sensitive material is exposed, usually expressed in feet per minute of printer operation.

prism: transparent body with at least two polished plane faces inclined with respect to each other, from which light is reflected or through which light is refracted. When light is refracted by a prism whose refractive index exceeds that of the surrounding medium, it is deviated or bent toward the thicker part of the prism. Prisms are often used for rotating an image.

processor: any machine which performs the various operations necessary to process photographic material.

projection: (1), formation of an image through optical means onto a sensitized surface or viewing screen, usually in magnified size; (2), image that is visible after it has been optically projected through space onto the surface.

projection lens: lens in an optical projection system which images the slide, film, etc. onto the screen. It is the lens closest to the screen.

projection printing (optical printing): method of exposing a photosensitive coating by projection of an image through an optical system.

projector: (1), optical system that projects images, usually magnified, on a viewing screen; (2), in lighting, a unit that by means of mirrors and lenses, concentrates the light to a limited solid angle so as to obtain a high value of luminous intensity.

proximity reflector (lamp): small non-focusing reflector located inside a lamp immediately behind a planar filament. See also **internal reflector.**

quartz-iodine lamp: see **tungsten halogen lamp.**

radiance: radiant flux per unit solid angle and per unit area measured normal to the direction of propagation of the flux. Also the radiant intensity of any surface (of a source, a receiver, or any other real or virtual surface) in a given direction per unit area of the surface as viewed from that direction. Units are watts per steradian and square centimeter (W/(sr.cm²)) and watts per steradian and square meter (W/(sr.m²)).

radiant: descriptor applied to electromagnetic radiation.

radiant density: radiant energy per unit volume; e.g., joules per cubic meter (j/m³).

radiant emittance: see **radiant exitance.**

radiant energy: energy traveling in the form of electromagnetic waves; electromagnetic radiation. It is measured in units of energy such as joules, ergs, or kilowatt-hours. See **spectral radiant energy.**

radiant exitance: density of radiant flux leaving a surface. It is expressed in watts per unit area of the surface. Formerly called **radiant emittance.**

radiant flux: rate of flow of radiant energy. Units are watts or joules per second.

radiant flux density at a surface: ratio of radiant flux at an element of the surface to the area of the element. Units are W/cm², W/m². Density of radiant flux emitted from a surface is called **radiant exitance** instead of the formerly used term radiant emittance. Density of radiant flux incident on a surface is called **irradiance.**

radiant intensity: radiant flux from a source per unit solid angle in a given direction. Units are watts/steradian (W/sr).

radiation: emission and/or propagation of electromagnetic energy; the electromagnetic energy being propagated.

radiator: emitter of radiant energy.

radiometry: measurement of quantities associated with radiant energy.

rapid-start fluorescent lamp: fluorescent lamp designed for operation with a ballast that provides a low-voltage winding for preheating the electrodes and initiating the arc without a starting switch.

rated life: average lamp life as determined on a group of lamps under controlled laboratory conditions of constant applied voltage, etc. Also, see **service life.** Life is generally defined as the time until the lamp fails to light; however for certain lamp types life is defined as the time until the lamp output falls to some given per cent of the initial output.

reader: projection device for viewing an enlarged microimage with the unaided eye.

reader-printer: machine which combines the functions of a reader and an enlarger-printer.

rear projection: projection of an image onto a translucent screen from the side opposite to that from which the image is viewed.

rear screen projection: technique of projecting an image onto a translucent screen with the projector on the side of the screen opposite the viewer.

reciprocity: in photography, the law stating that the exposure (i.e., optical density with standard development) of sensitized material is the product of **illuminance** and time, i.e., the amount of light absorbed, and is independent of **intensity.**

reciprocity law: the reciprocity law of Bunsen and Roscoe states that exposure is equal to the intensity (irradiance) of the exposing energy multiplied by the time during which it acts. This law is only approximately followed by photographic materials and deviations from it are known as 'reciprocity law failures'.

reciprocity failure: deviation of the exposure of sensitized material from that predicted by the law of **reciprocity** outside a certain range of intensities.

reduction: measure of the number of times a given linear dimension of an object is reduced when photographed, expressed as 16X, 24X, etc.

reduction ratio: ratio of the linear measurement of a document to the linear measurement of the image of the same document expressed as 16:1, 20:1, etc.

reference copies: microfilm copies, usually of the second or higher generation, made from camera microfilm, intermediates, or distribution copies; reference copies are usually not accountable and are sometimes called 'non-returnable' or 'throw-away' copies.

reflectance: ratio of reflected flux to incident flux. Unless otherwise specified, total (hemispherical) reflectance is meant. Since measured values of reflectance depend upon the angles of incidence and view and on the spectral character of the incident flux and of the detector, the geometry and the spectral characteristics of the source and detector should be specified. See **reflection.**

reflection: process by which incident flux is returned by a surface or medium. Reflection may be regular (specular), diffuse, or a combination. See **regular (specular) reflection.**

reflector: device used to redirect the flux from a source by the process of reflection.

reflector lamp: lamp with partially reflectorized bulb to increase intensity in desired directions.

refraction: process by which the direction of a ray of light changes as it passes obliquely from one medium to another having a different refractive index.

refractive index: see **index of refraction.**

device used to redirect the flux from a source, primarily by the process of refraction.

regular (specular) reflectance: ratio of the flux leaving a surface or medium by regular (specular) reflection to the incident flux. See **regular (specular) reflection.**

regular (specular) reflection: process by which incident flux is redirected at an angle (the specular angle) equal to the angle of incidence.

regular transmission: process by which incident flux passes through a surface or medium without scattering. See **regular transmittance.**

regular transmittance: ratio of regularly transmitted flux leaving a surface or medium to the incident flux.

relative luminosity: previously used term for **spectral luminous efficiency of radiant flux.**

relative luminosity factor: previously used term for **spectral luminous efficiency of radiant flux.**

reproducible: document or copy which is sufficiently translucent to be used to make further contact copies.

reprography: the art and science of reproducing documents.

resolution: ability of optical systems and photomaterials to render visible fine detail of an object; a measure of sharpness of an image, expressed as the number of lines per millimeter, discernible in an image. Resolution in processed microfilm is a function of film emulsion, exposure, camera lens, camera adjustment, camera vibration, and film processing. Resolution is measured by examining a microfilmed resolution test chart under a microscope to determine the smallest pattern in which lines can be distinguished both horizontally and vertically.

resolving power (photographic): degree to which a lens, optical system, or film emulsion is able to define the detail of an image, expressed as the number of lines per millimeter discernible in an image.

retrieval, information: recovering of desired information or data from a collection of documents or other records. The term information retrieval is the generic term which includes reference, document, and fact retrieval.

reverse reading: a term used to define a reproduction which is a mirror image of the original regardless of whether that image is rotated with respect to the original.

rewind: (1), device consisting of a spindle geared to a crank, used in pairs to wind film from one reel to another; (2), act of transferring film from one reel to another to obtain a different orientation of the film.

right reading: image which is legible in a normal reading position, regardless of whether it is rotated with respect to the original.

roll microfilm: length of microfilm on a reel, spool, or core.

root-mean-square (rms): square root of the average of the square of the magnitude of a periodic function taken over one period. In electrical usage, the rms value of an ac voltage or current was previously called the effective value because it had the same heating effect as a dc voltage or current of the same rms value.

safelight: darkroom light source required to give maximum visual intensity with little or no effect on photographic materials.

saturation of a perceived light source color: attribute used to describe the departure of a perceived light-source color from a light-source color of the same brightness perceived to have no hue. See **saturation of a perceived object color.**

saturation of a perceived object color: attribute used to describe the departure of a perceived object color from gray of the same lightness.

scale, gray: array of adjacent neutral gray density areas varying by a predetermined stepwise ratio from black to white and used to control the contrast of photographic duplicates. A step tablet or gray wedge. Continuous-gradient gray scales, showing no perceptible steps, are also used for special purposes.

scotopic vision: vision by means of the retinal rods. It is generally associated with adaptation to a luminance below about 0.01 footlambert. See **photopic vision, dark adaptation.**

screen: surface onto which an image is projected.

screen gain: ratio of the luminance of a screen to the luminance of a reference screen which (1) reflects all of the incident light and (2) reflects it uniformly in all directions, i.e., has a uniform luminance in all directions. The gain of an actual screen will vary with the viewing direction, and may be greater than unity over a limited range of directions. The concept may be applied to rear projection screens by considering transmission rather than reflection.

screen lumens: quantity of light flux reaching a screen from a projector.

seasoning: short burn-in time on a new lamp before measuring initial lumens. This avoids rating lamps before they have stabilized. See **initial lumens.**

self-ballasted lamp: electric discharge lamp with an integral current-limiting device. See **blended lamp.**

sensitivity: degree to which an emulsion reacts by the formation of a latent image under given exposure conditions, especially as this relates to exposure by different wavelengths (colors) of light.

service life: lamp life in service as affected by voltage variations, vibrations, shock, excessive heat conditions, etc. See **rated life.**

sharpness: degree of line clarity.

shutter: mechanical device which regulates the time that light is permitted to act upon sensitized film or paper.

shutter speed: length of time in which light is permitted to act upon film or paper as a result of the shutter having opened and closed.

simplex: image orientation where each image is photographed across the full width of the film.

slow emulsion: photographic layer having moderate or relatively low sensitivity to light.

sodium lamp: electric discharge lamp employing sodium vapor. See **high-pressure sodium lamp, low-pressure sodium lamp.**

soft: term applied to photographic emulsion or developer having low contrast.

soft copy: enlarged copy usually on a reader screen.

soft glass: glass having a relatively high coefficient of thermal expansion (about 70×10^{-7} °C^{-1}) and a softening temperature on the order of 600°C. See **hard glass.**

solid angle, ω: measure of the space about a point and included within a conic surface having its apex at that point. Quantitatively, the ratio of the area on the surface of a sphere intercepted by the conic surface to the square of the radius of the sphere. It is expressed in steradians (sr).

spectral distribution: spectral radiant power ($dP/d\lambda$) or energy ($dQ/d\lambda$) as a function of wavelength.

spectral energy distribution (SED): plot of energy output versus wavelength for a flash of light from a chemical flash lamp or an electronic flash lamp. The area under the curve equals the total *radiated* joules in the flash. See **spectral power distribution.**

spectral luminous efficacy of radiant flux: ratio of the luminous flux at a given wavelength to the radiant flux at that wavelength. It is expressed in lumens per watt. See **spectral luminous efficiency of radiant flux** and **luminous efficacy of radiant flux.** Formerly called luminosity factor.

spectral luminous efficiency of radiant flux: ratio of the luminous efficacy at a given wavelength to that at the wavelength of maximum luminous efficiency. The functions giving the spectral luminous efficiency of radiant flux are designated $V(\lambda)$ for **photopic vision** and $V'(\lambda)$ for **scotopic vision.** Formerly called **relative luminosity** and **relative luminosity factor.**

spectral power distribution (SPD): plot of power output versus wavelength. For continous sources the area under the curve represents power since the plotted function is $dP/d\lambda$. Simultaneous line radiation (e.g., fluorescent lamps) is shown by the artifact of representing the line power distributed over a small finite bandwidth such that the power of the line is the area under the curve in that bandwidth.

spectral radiant energy: radiant energy per unit wavelength interval.

spectrum locus: locus of points representing monochromatic radiation throughout the visible spectrum on a chromaticity diagram.

specular surface: one from which the reflection is predominantly regular. See **regular (specular reflection.**

speed: common term for sensitivity of a photographic layer, maximum aperture of an objective lens, chemical efficiency of a processing solution, or the timing of a shutter. The 'speed' of film is established by ANSI procedures and is generally based on the reciprocal of the exposure required to produce a certain fractional gradient or density.

speed of light: the speed of all radiant energy including light is 2.997925×10^8 meters per second in vacuum (approximately 186,000 miles per second). In all material media the speed is less and varies with the material's index of refraction, which itself varies with wavelength and physical state.

standard source: light source having a spectral distribution specified by the CIE. In 1931 the CIE specified the spectral energy distributions for three standard sources, A, B, and C. Recently standard source D_{65} has been added.

standard source A: a tungsten-filament lamp operated at a color temperature of 2856K and approximating a blackbody operating at that temperature.

standard source B: an approximation of noon sunlight having a correlated color temperature of approximately 4874K. It is obtained by a combination of Source A and a special filter consisting of a layer one centimeter thick of two specified solutions contained in a double cell constructed of non-selective optical glass.

standard source C: an approximation of daylight provided by a combination of direct sunlight and clear sky having a correlated color temperature of approximately 6774K. It is obtained by a combination of Source A plus a double cell identical with that used for Source B, except that two different solutions are specified.

standard source D_{65}: an approximation of daylight at a correlated color temperature of 6500K. It is defined by its relative spectral power distribution over the range from 300 to 830 nanometers.

starter: device used in conjunction with a ballast for the purpose of starting an electric-discharge lamp.

Stefan-Boltzmann law: statement that the total radiant exitance of a blackbody is proportional to the fourth power of its absolute temperature.

step tablet (step wedge): length of film containing gradations of density, which may or may not be calibrated. A calibrated step tablet is used as a standard in the calibration of a densitometer.

steradian, sr: unit of solid angle. See **solid angle.**

stilb, sb: unit of luminance equal to one candela per square centimeter (1cd/cm²).

stopping down (stop down): to reduce the size of a lens aperture.

strip film: length of film too short to be wound on a reel, which is generally housed in a small can called a 'strip can', or inserted in a jacket or other type of holder.

strobe: term generally used for **electronic flash** (q.v.).

subjective brightness: attribute of any light sensation giving rise of the precept of luminous intensity, including the whole scale of qualities of being bright, light, brilliant, dim, or dark. Note: The term **brightness** (q.v.) often is used when referring to the measurable **photometric brightness.** The currently accepted term for the photometric quantity is **luminance,** thus reserving brightness for the subjective sensation.

subtractive color mixture: color produced by absorption of various wavelengths from white light by means of two or more absorptive colorants (e.g., dyes or pigments), each of which selectively absorbs certain wavelengths that the other colorants reflect or transmit. A range of desired colors may be produced by combining the three subtractive primary colorants (e.g., magenta, cyan, and yellow) in the correct proportions. See **additive color mixture.**

t-number: ratio of the f-number of a lens to the square root of the transmittance of that lens. The t-number of a lens equals the f-number of an ideal lens having 100 percent transmittance and giving the same central illuminance as the real lens.

talbot, T: unit of light energy to one lumen-second.

target: (1), any document or chart containing identification information, coding, or test charts; (2), an aid to technical or bibliographic control which is photographed on the film preceding or following the document.

temperature radiator: radiator whose radiant exitance is determined by its temperature and the material and character of its surface. See **blackbody, graybody.**

tempered glass: glass treated by heating and then chilling. The resulting internal stresses cause compression of the surfaces. This pre-stressing strengthens the glass because the compression must be overcome to break the glass, which fails only in tension.

thermal radiator: see **temperature radiator.**

thin film: general term for one or more thin layers of metal or dielectric deposited on the surface of an optical component to provide protection or to alter the spectral and/or total transmittance or reflectance.

throughput: product of the cross-sectional area of a light beam and the solid angle included by the beam. This is a geometric measure of the maximum power that can be transferred by an optical system which is 'fully-flashed' by a source. The power transferred by a not-fully-flashed optical system can be increased by increasing the source size and/or radiance (or luminance); but when the source size is increased to that at which the optical system is fully flashed, the power transferred by the system cannot be further increased by increasing the source size, but only by increasing the source radiance (or luminance). Throughput is expressed as radiant flux per unit radiance, or as luminous flux per unit luminance, and the units are square meter-steradian. Also called etendue or geometric extent.

time-light characteristic: plot of light output of a flash lamp versus time.

torr: unit of pressure equal to 1/760 of a standard atmosphere. (1 atm = 760 torr).

trailer: that portion of film beyond the last images recorded.

translucent: having the property of diffuse transmission.

translucent screen: sheet of treated glass (ground, coated, etc.) or plastic used to form a visible image in microfilm readers. The image is projected onto the back of the screen and viewed from the front.

transmission: process by which incident flux leaves a surface or medium on a side other than the incident side. Transmission through a medium is often a combination of regular and diffuse transmission. See **regular transmission, diffusion,** and **transmittance.**

transmittance: ratio of transmitted flux to incident flux. Measured values of transmittance depend upon the angle of incidence, geometry of collection for the transmitted flux, and the spectral character of the incident flux and of the detector. Because of this dependence, complete information on the technique and conditions of measurement should be specified. Since transmittance refers to the ratio of emerging flux to incident flux, reflections at the surface as well as absorption within the material operate to reduce the transmittance.

transparency: image on transparent base stock which may be viewed by transmitted light, or used to make copies.

transparent: having the property of **regular transmission.**

tristimulus values, X, Y, Z, of a light: the amounts of each of three primaries required to match the color of the light.

tristimulus weighting function, $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$: color matching responses of an observer to three primaries having equal spectral power.

tungsten-halogen lamp: tungsten-filament incandescent lamp with an inert gas fill containing a small proportion of halogen vapor. The bulb is usually made of fused silica or high-silica glass to withstand the high temperatures and pressures required for operation of the halogen cycle which reduces evaporation of tungsten from the filament and deposition of tungsten on the bulb wall. Formerly called **quartz-iodine lamp.**

ultra high reduction: microform reduction above 90x.

ultrafiche: microfiche with images reduced more than 90X. See **microfiche, ultra-high reduction.**

ultraviolet radiation: radiant energy in the wavelength range 10 to 380nm. This includes black light (320-380nm), erythemal radiation (280-320nm), bactericidal or germicidal radiation (220-300nm), and ozone-producing radiation (180-220nm). There are no sharp demarcations between these bands, the indicated effects usually being produced to a lesser extent by longer and shorter wavelengths.

underdevelop: insufficient development of sensitized material due to developing for too short a time, use of a weakened developer, or too low a temperature.

underexpose: insufficient exposure of sensitized material due to insufficient illumination, too short an exposure time, or too small a lens aperture.

Underwriter's Laboratories (UL): an independent testing laboratory that will test equipment to see if it meets certain safety standards when properly used.

USASI: See **American National Standards Institute.**

veiling reflection: reflections from an object that partially or totally obscure the details to be seen by reducing the contrast. This sometimes is called reflected glare.

very high reduction (vhr): microform reduction above 60X up to and inclusive of 90X.

vesicular film: film which has the light-sensitive element suspended in a plastic layer and which upon exposure creates strains within the layer in the form of a latent image. The strains are released and the latent image made visual by heating the plastic layer. The image becomes permanent when the layer cools.

wavelength: distance between two successive points of a periodic wave in the direction of propagation, in which the oscillation has the same phase. Units are meter, micrometer (1m = 10^{-6}m) and nanometer (1 nm = 10^{-9}m).

width direction: direction of the film or paper at right angles to the forward movement in the film or papermaking machine.

Wien displacement law: expression representing the spectral radiance of a blackbody as a function of its wavelength and temperature. The two principal corollaries of this law are that the maximum spectral radiance varies as the fifth power of the absolute temperature, and that the wavelength of maximum spectral radiance varies inversely as the absolute temperature.

xenon lamp: electric-discharge lamp using xenon gas to generate light. There are two major types: the xenon short-arc lamp is a continuous source, and the xenon flashtube is an intermittent source.

xerography (electrostatic): generic term for the formation of a latent electrostatic image by action of light on a photo conductive insulating surface. The latent image may be made visible by a number of methods such as applying charged pigmented powders or liquids which are attracted to the latent image. The particles either directly or by transfer may be applied and fixed to a suitable medium.

zonal constant: constant by which average intensity for a solid-angle zone of a source is multiplied to give lumen output of the source in that zone. They are widely tabulated for various geometries of photometric measurements.

zonal lumens: luminous flux of a lamp in a specified angular zone.

zonal lumen-seconds: luminous energy output of a photoflash lamp in a specified angular zone. Used for photoflash lamps with built-in reflectors.

zoom lens: lens with movable optical elements which can retain an object in focus while changing the lens focal length. Consequently, the size of the object can be varied while the camera or reader remains in the same position.

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